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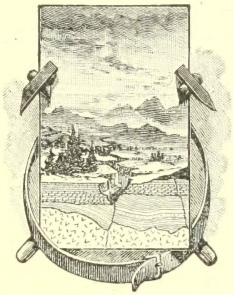

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DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
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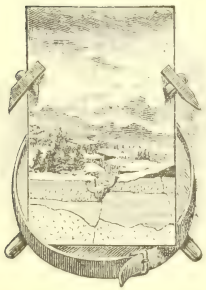
WATER-SUPPLY PAPER 257

WELL-DRILLING METHODS

BY

ISAIAH BOWMAN



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WELL-DRILLING METHODS.

By Isaiah Bowman.

INTRODUCTION.

PURPOSE OF REPORT.

The following report on methods of well drilling deals with a subject which should interest both the geologist and the engineer, for well drilling lies in that borderland where geology and engineering meet on equal terms. The resulting dual nature of the problems involved is best illustrated by the class of men who are constantly being called into consultation in regard to them. These men are either geologists who have had experience in water-supply problems, engineers who are somewhat familiar with geology, or men who, recognizing the special nature of the problems involved, are conversant with both geology and engineering.

During the last ten years there have been many demands for a publication on well drilling, and this report is the result of an attempt to meet these demands. The need of such a report has been increased by the fact that no adequate treatment of the subject is given in any available American publication. There are several old English texts on well drilling, and a book dealing mainly with modern English methods has been published.[a] An excellent and comprehensive work has appeared on the conditions met and the methods used in the Baku oil region of Russia, on the shores of the Caspian Sea,[b] and there are a few books and reports on oil-well and gas-well construction and care. Scattered accounts of methods employed in certain localities have also appeared in engineering journals. The trade catalogues of companies manufacturing the various kinds of well-sinking machinery contain very good descriptions of their special outfits, but no publication presents a coordinated account of the various methods of well sinking and their application to wells constructed for different purposes and under different geologic conditions.

The field studies that form the basis of the present report were undertaken in connection with ground-water investigations made in the

[a] Isler, C., Well-boring for water, brine, and oil. 1902.
[b] Thompson, A. Beeby, The oil fields of Russia, 1904; 2d ed., 1908.

eastern United States. These studies extended over a period of three years and included actual observations of well drilling in many parts of the eastern half of the country, and were supplemented by one season's observations in the South and in the Middle West.

METHOD OF TREATMENT.

The driller deals with rocks as well as with tools, and to be successful he must understand the character and attitude of the rocks as well as the manipulation of the tools. As by far the most common object of well drilling is to obtain water, oil, or gas, this report deals with the occurrence of these products and thus meets the desire among drillers for information that will enable them to select well sites with as definite an idea as possible of the rock formations that may be encountered. The report does not, however, take up the geologic relation of ore deposits and the methods of ore prospecting with drills, for such a discussion would involve the whole subject of structural and metamorphic geology and ore deposition.

After the oil and gas-bearing relations are discussed a short account of the development of well construction is given, and then the methods of drilling and boring are described in detail. The chief uses and general features of each method are discussed, the different parts of the outfit, its modifications, and its operation are described, and the more common difficulties encountered in its use are stated, together with the classes of material to which each method is best adapted.

The less familiar methods as well as those commonly used are discussed, for though the unusual methods are of restricted use and, owing to changed economic conditions, have been superseded by other methods in many localities where they were formerly much employed, they can be successfully used in new territory where the conditions are similar to those that once existed in the older fields. The presentation of these now generally obsolete methods may therefore enable drillers in the newer parts of the country or in the island possessions to meet advantageously the conditions existing in those regions. Two specific examples may be mentioned in illustration of this point. Throughout central Texas, Oklahoma, and parts of Kansas water wells are sunk by portable churn drills operated by horsepower. Horsepower is now obsolete in the East, where it has been superseded by steam, but in the Southwest, where coal is scarce and transportation rates are high, horses are plentiful and cheap and horsepower is more economical than steam. From Mississippi and Alabama many orders come to northern and eastern supply houses for well-drilling or well-boring outfits that can be operated by hand for sinking shallow water wells. Here, again, the reasons for retaining the old-style outfit are clear. In these States fuel is costly and horses are not plentiful, but labor is cheap, so that although the machine

in use is primitive, it meets the conditions better than any more elaborate device.

The treatment of the separate methods is followed by a discussion of a number of special features of well construction and a few general estimates of the cost of well sinking. Though figures showing cost can be only approximate, because local conditions are important factors in their determination, they at least afford some indication of the expense of well construction or of prospect work by the ordinary methods of drilling and boring.

ACKNOWLEDGMENTS.

The preliminary discussions of rainfall, underground water, and water-bearing formations (pp. 9–21) have been compiled chiefly from a paper by M. L. Fuller.[a]

For assistance in collecting material for this report the writer is indebted to well owners, drillers, and representatives of supply companies throughout the country who have cooperated in its preparation with unfailing courtesy and good will. Individual mention is made in the body of the report of those who have given special aid in the work. Some of these men have taken great trouble and incurred considerable expense to procure data that are of great general importance though of no immediate practical benefit to themselves. At the end of the report is given a list of the supply companies that have assisted in bringing it up to date by furnishing estimates and descriptions and by giving permission to reproduce illustrations and other copyrighted material. Any failure in the report to meet the practical needs of drillers and others interested in the development of underground resources is not due to lack of interest and support on the part of those who have thus cooperated with the author.

UNDERGROUND WATERS OF THE UNITED STATES.

AMOUNT AND DISTRIBUTION OF RAINFALL.

Practically all the water encountered in well drilling is derived from rainfall. Its amount and its disposal and the conditions of its occurrence in the rocks will therefore be briefly considered.

In the eastern United States the rainfall is plentiful, the yearly average varying from 20 to nearly 70 inches. (See fig. 1.) Rain to a depth of more than 60 inches a year falls on the Mississippi Delta below New Orleans, and along the Gulf coast from near Mobile, Ala., to Tallahassee, Fla. A nearly equal amount falls in the higher mountains of western North Carolina and eastern Ten-

[a] Fuller, M. L., Underground waters of eastern United States: Water-Supply Paper U. S. Geol. Survey No. 114, 1905, pp. 18–40.

nessee, along the coast of North Carolina, and in the Adirondack and White mountains. In the Gulf and South Atlantic States the rainfall is between 50 and 60 inches a year; in the New England, Central Atlantic, and Ohio River States, between 40 and 50 inches; in the upper Mississippi and Great Lake States, between 30 and 40 inches; and in northwestern Iowa and most of Minnesota, between 20 and 30 inches.

In the western part of the United States the distribution of the rainfall is much more irregular than in the eastern part. Westward from a line drawn through the eastern part of the Dakotas, middle Nebraska, western Kansas, and central Texas the rainfall decreases to less than 20 inches yearly, all of the Great Plains region being characterized by small rainfall. In the Black Hills, the Bighorn

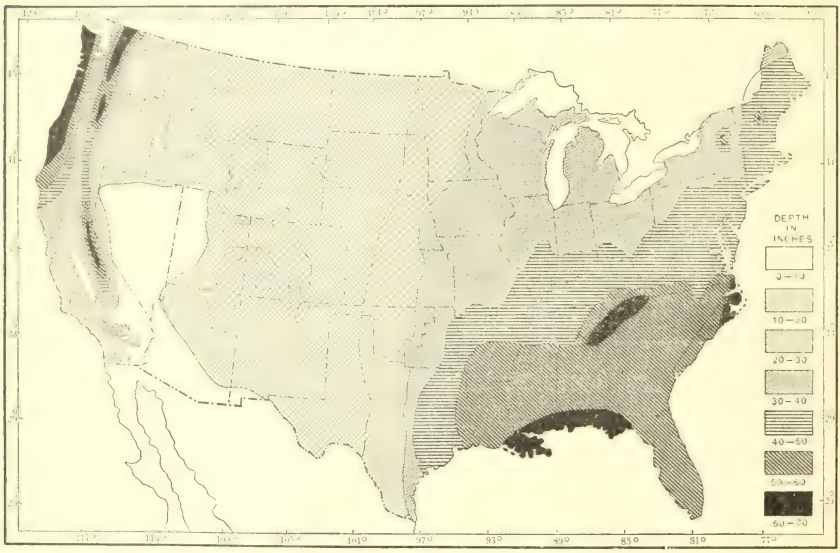


FIGURE 1.—Map showing mean annual rainfall of the United States.

Mountains, and the higher sections of the main chains of the Rocky Mountains the rainfall is 20 or 30 inches yearly; and in the high Sierra, the Cascades, and the Coast Ranges it is 70 inches or more, reaching a maximum of 150 inches in the Coast Ranges of Oregon. In the Great Basin region, between the Sierra Nevada and the Wasatch Mountains, the rainfall is less than in any other section of the country, in places being as low as 2 or 3 inches a year.

DISPOSAL OF RAINFALL.

RUN-OFF.

The greater part of the precipitation on most areas is disposed of directly by run-off through surface streams. The direct run-off

can sometimes be determined, but, owing to the intimate relations of stream flow to the ground supply from which streams draw much of their water, it is seldom practicable to determine the run-off for large areas. In arid regions, where the surface deposits are porous, the run-off is relatively small, but, owing to the fact that rain in these regions falls chiefly in sudden downpours, the annual run-off is not so small as would be indicated by the small annual precipitation. In humid regions and in places where the surface is composed of impervious materials the run-off is greater. Frozen, snow-covered, and ice-covered ground yield especially large flood flows. Over frozen areas nearly all the rain water may at once join the streams, whereas in some sandy regions practically all the precipitation is absorbed by the soil. In the eastern half of the country the run-off will probably not average more than 20 per cent of the rainfall. In the West, although the percentage of run-off in small areas is at times great, it is on the whole less than in the East, for much of the water that is not taken up directly is later absorbed from the streams by the dry, sandy soils.

EVAPORATION.

Owing to the great humidity of the atmosphere during storms, evaporation while rain or snow is falling is small. Snow may remain on the ground a long time, and, as a rule, is evaporated to a greater degree than rain, especially during periods of sunshine and warm winds that follow storms. The evaporation from different areas also differs greatly. From forest-covered soils it is relatively small; from open plains it is relatively large.

ABSORPTION.

AMOUNT.

The rain water that is not evaporated immediately or carried off by streams sinks into the ground. The ground receives the greater part of the rainfall, probably nearly 80 per cent in the eastern United States and 90 or 95 per cent in much of the West. Absorption by the underlying rocks takes place both directly and indirectly. Rain may fall on the surface of the rocks and be absorbed in their pores, fissures, and cavities, or it may be first absorbed by loose, unconsolidated surface deposits and afterwards carried down into the rocks, or it may be gathered into streams that flow over rock surfaces and from these gradually absorbed by the underlying rocks. The amount of rainfall that the rocks absorb indirectly is far greater than that which they absorb directly.

Water that enters sands and gravels generally moves toward the streams rather than away from them, but in regions where the rain-

fall is small the gravels may absorb water from the streams which rise in regions of greater rainfall.

FACTORS INFLUENCING ABSORPTION.

Structure.—The readiness with which water enters the underlying rocks is influenced largely by the structure of the rock beds or layers. In areas that are level or gently sloping the exposed areas of water-bearing beds that are not greatly inclined will be much greater than the exposed areas of beds that dip steeply and will therefore absorb a greater amount of water. (See fig. 2.)

Porosity.—The pore space between the particles that constitute a rock—that is, the porosity of the rock—may in a general way be determined by the quantity of water which the rock will absorb. This quantity differs greatly with different kinds of rock, being least in compact igneous rocks and greatest in sandstones and loose sands.

FIGURE 2. Diagram showing relation of areas of outcrop to dip. *a b*, Outcrop of steeply dipping stratum; *a' b'*, outcrop of gently dipping stratum.

The following table shows approximately the amounts of water absorbed by sand and by some common rocks.

Absorptive capacity of rocks in quarts of water per cubic foot.[a]

Sand	10
Potsdam sandstone	2–6
Triassic sandstone	4
Trenton limestone	$\frac{1}{4}$–$1\frac{1}{4}$
Dolomite	1–10
Chalk	8
Granite	$\frac{1}{10}$–$\frac{1}{4}$

Solution caverns.—In some regions water enters the ground in definite streams through caverns or other passages formed by the solution of limestone or other soluble rock. Water commonly enters limestone through depressions called sink holes, or "sinks," due to the falling in of the roofs or walls of caverns which have been formed by underground streams, or by the enlargement by solution of cracks or joints in the rock. These sinks maintain connection between the surface and the underground channels, water flowing into them and passing downward to become a part of the underground supply.

Faults.—Faults are displacements along fractures that cut the rock. Some faults consist of single planes, with solid walls on each side, but many of them are formed of a number of parallel fractures, very

[a] Water-Supply Paper U. S. Geol. Survey No. 114, 1905, p. 23.

close together, along which there has been displacement. The rock on both sides of many faults is crushed and the fragments are more or less disturbed with relation to one another. Some fractures are irregular, and the broken rock has been so moved that projecting masses come opposite one another, leaving intervening cavities into which water may penetrate.

Bedding planes.—Bedding planes, separating layers of stratified rock, may afford openings for underground water. The planes in igneous rocks along which two kinds of rock come in contact may afford similar openings. In each the movement of water is rendered easy either by the open space formed along the planes or by the contact of porous and impervious materials or by both of these causes.

Joints.—Joints are smooth fractures that cut the rock in various directions. They therefore correspond most nearly to single faults, but they differ from faults in that there has been practically no movement of the rock along them. Like faults, they present conditions that are relatively favorable to the entrance of water, especially at the intersection of two or more joints.

In the Connecticut Valley, after a rainstorm, one may see on the faces of cliffs of jointed trap rock evidences of the water-holding capacity of joints. These cliffs are darkened at the joints for hours or even for days after the rain has ceased by the escape of accumulated water, while the rest of the cliff is quickly dried under the action of the sun and wind and presents its usual appearance.

Cleavage planes.—Cleavage consists of minor fractures that cut the rock. Unlike joints, cleavage planes usually run in only one direction, and are frequently not actual fractures, but simply lines of weakness, along which the rock tends to split. Cleavage is best developed in fine-grained compact rocks, of which roofing slate is a good example. Cleavage planes do not afford as ready passage for water as do the other structures described.

Foliation and schistosity.—Foliation and schistosity are due to the presence in rock of minerals that occur in thin, plate-like crystals that lie parallel to one another. In many places water passes readily into the rock along planes formed by layers of these crystals.

AMOUNT OF UNDERGROUND WATER.

A part of the underground water which has reached the lower levels occupies spaces along bedding, fault, joint, and other planes, and a part occupies solution channels and caverns formed in soluble rock. The several kinds of fractures mentioned, although very numerous in the aggregate, nevertheless comprise only a small portion of the open space within rock. The pores between the particles that make up the rock are, on the contrary, everywhere present throughout the entire mass and constitute by far the largest part of

the open space within it. The pore space thus affords the best reservoir for the storage of water.

In most places it is necessary to penetrate some distance below the earth's surface in order to reach a zone saturated with water, the actual depth depending on the amount of precipitation, the character of the rock, and the topography.

This depth is least in regions of much rainfall and greatest in arid regions; and in general it is least in valley bottoms and greatest in the higher lands. In some localities, as at springs and in marshy lands, the plane of saturation coincides with the surface, but the existence of ground water at the surface is due to exceptional conditions.

The lower limit of penetration of water depends on a number of conditions. The limit to which water will penetrate is the depth at which the weight of the overlying rock becomes so great that pores between the particles can not exist. This depth has been theoretically placed at about 6 miles. Practical experience in well drilling, however, does not approve the assumption that all rocks are saturated below a moderate depth. In the Pennsylvania and the New York oil regions, for instance, rocks that are practically destitute of water are encountered at a depth of only a few hundred feet. These rocks include coarse-grained sandstones capable of holding large amounts of water, yet as far as can be determined they are quite dry, so that it is necessary in some wells to pour in from the top the water required in drilling. In some parts of these oil fields the drill enters rocks containing salt water after passing through these water-free rocks; but very rarely is fresh water found below the dry rocks. In some places wells have been drilled several thousand feet deep without encountering water below the first few hundred feet; but, although the rocks thus penetrated are far from being saturated, they doubtless hold slight amounts of moisture. These facts show the fallacy of the popular idea that there is plenty of water if one only goes deep enough, and that great underground lakes exist.

Although the depth to which water penetrates in large quantity is much less than is frequently assumed, the ground contains, nevertheless, an enormous amount of water. Many estimates of the amount of ground water have been made, all of which take into account only the free water (that which is or might be available for pumping purposes) and do not include that which is contained in moist clays and other materials and is not readily yielded to wells. These estimates have become more and more moderate, ranging from that of Delesse, made about 1860, which showed a layer sufficient to cover the surface of the globe 7,500 feet deep, through that of Slichter (1902) which showed a similar layer 3,000 to 3,500 feet deep, and of Chamberlin and Salisbury (1904) which gave a

layer of 800 to 1,600 feet thick, to that of Fuller[a] (1906), which shows that the amount of water available in the earth's crust is sufficient to form a layer over the surface of the globe a little less than 100 feet deep. This amount is equivalent to about $\frac{1}{100}$ part of the volume of oceanic water.

ARTESIAN CONDITIONS.

The requisite conditions for artesian water are fewer in number than is usually supposed, and some artesian flows are found under circumstances which are considered anomalous. The conditions for artesian flow are clearly stated by Veatch,[b] who says:

Underground water in passing downward may go beneath a relatively impervious layer which tends to confine it and produce a hydraulic head. In this respect underground waters differ from surface waters, which are always free on one side and can not, except where artificially confined, as by closed flumes, produce analogous phenomena. This natural confinement of the ground water causes water in wells to stand above the porous layer in which it is

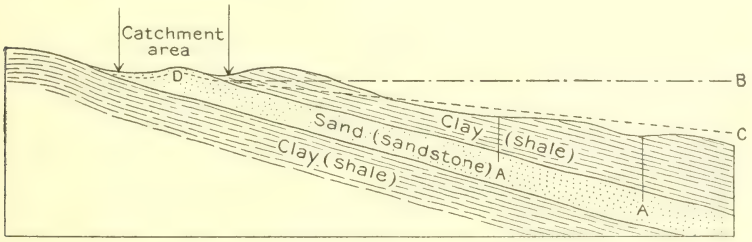


FIGURE 3.—Diagram showing ordinary conditions producing artesian wells. A, Artesian wells; B, head of water if there be no loss by resistance and leaking; C, actual head or hydraulic gradient; D, ground-water table at outcrop.

encountered and is of vast economic importance, especially in arid regions, where the water is very deep seated and has been transferred from a region of more bountiful rainfall.

In order that a well may flow it is necessary that the following conditions be satisfied:

1. There should be sufficient rainfall.
2. There should be relatively porous beds suitably exposed to collect and transmit the water.
3. There should be less porous or relatively impervious layers so placed that they may confine the water collected.
4. The level of the ground water at the source should be at a sufficient height above the mouth of the well to compensate for the loss of head due to resistance and leakage.

The arrangement of the factors which produce a flow is by no means constant. These factors vary considerably from point to point, and relatively new combinations are to be constantly expected. Probably the commonest combination is that shown in the accompanying diagram [fig. 3]. Here the confining beds are clay

[a] Fuller, M. L., Total amount of free water in the earth's crust: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, pp. 59–72.

[b] Veatch, A. C., and others, Underground water resources of Long Island, New York: Prof. Paper U. S. Geol. Survey No. 44, 1906, pp. 54–55.

and the porous bed is a sand which dips regularly in the direction in which the surface slopes. Water falling in the region marked "catchment area" sinks into the sands and supplies the artesian wells on lower ground.

The foregoing conditions may be taken as typical of a large class of artesian wells and are perhaps those more commonly described and understood, but flows may be obtained under several modifications of the conditions described, though they depend on the same general principles.

WATER-BEARING FORMATIONS.

GEOLOGIC CONSIDERATIONS.

Geologic knowledge has perhaps no greater practical value than in the study of the occurrence of underground water and in the selection of sites for drilled wells. In many places the selection of the location for a well is so restricted that there is practically no choice at all. Yet, though water supplies for public buildings and institutions are usually required on the premises, it may often happen that if the site had been shifted a few yards water would have been reached at much less depth; or if it had been moved down the dip of the strata a short distance flowing water would have been tapped and pumping would have been avoided.

The locating of wells is subject to so much superstition and guesswork among drillers and prospective well owners that it seems worth while to point out a few general principles that should control.

Many of the details that influence the presence of underground water can be intelligently determined only by means of an examination of the region in which the well is to be sunk and a careful analysis of observations of other wells put down in the locality. The observing well driller will furthermore take into account the surface drainage of the region, the presence or absence of forest lands which may influence the rate and amount of run-off, the existence of springs as evidence of surplus water at given points, and the depth and character of soil overlying the rock. Especially will he consider the structure of the soil cover, for it may be water-laid and therefore stratified and regular in its formation, so that an accurate and quick deduction can be made as to the depth and availability of the ground-water supplies; or it may be wind-laid and therefore less regular; or, in regions covered with material deposited by ice it may be still more irregular. All ground water, however, has a more or less intimate relation to the surface drainage and the topography.

Even after the most thorough investigation of the surface geology, however, there is always a certain degree of chance in the results of the first well drilled in a region. The variations from conditions predicted are, as a rule, small, or even insignificant, but occasionally they are great, as the projectors of the Simplon tunnel discovered

when they encountered unexpected volumes of heated water. Therefore the conclusions of a competent geologist are to be considered by the well driller as a moderately safe guide in a new region, one which will enable him to determine roughly the possibility of obtaining water, the method of drilling to be employed, and the length and kind of casing that will be required. More reliable geologic inferences, however, can be drawn only after some drilling has been done in the region; so that the geologist and the driller must supplement each other.

CLASSES OF MATERIAL.

SANDS AND GRAVELS.

Beds of sand and gravel are very porous, as much as 30 per cent of the volume of some of them being made up of free space, so that saturated layers that are penetrated by wells yield copious supplies of water. This water is in most places of good quality, but in some wells it is greatly mineralized with salts derived from the more soluble rock fragments that constitute the deposits.

In passing downward through sands, especially the finer varieties, surface water may be naturally filtered so that substances with which it may have been polluted are removed. In coarse sands and in gravels the water passes downward more rapidly and the conditions are less favorable for its filtration, so that it may remain polluted. In general, however, water derived from sands and gravels that lie a considerable distance below the surface is pure.

Because of the readiness with which sands and gravels yield their water, wells that are sunk close together in them may affect one another, the deeper wells, or those which derive their supply from the sands at the lowest points, drawing the water from the shallower wells. The readiness with which the water moves is also the cause of important fluctuations in the level of the surface of the saturated zone, as the water level may fall rapidly after wet seasons. To procure permanent supplies a well should penetrate below the level to which the water surface falls in the driest season.

CLAY.

Pure clay is nearly impervious to water and contains little or none that can be utilized as a source of supply. Water is frequently reported in clay, but as a rule it comes from more or less sandy layers within a clay bed. In some places sand that approaches clay in fineness and that is sometimes mistaken for clay yields considerable amounts of water. Clay is of great importance in connection with underground water, not directly as a water-bearer, but as a confining layer to porous sands from which it prevents the water from escaping.

Because of the fineness of clay the water it contains comes into contact with a relatively large amount of mineral matter and may become mineralized, especially by lime and salt, but as a rule it is free from contamination by the organic substances that cause typhoid fever and other diseases.

When it is necessary to obtain water from clay the well should be as large as practicable and should be carried deep enough to provide ample storage capacity, for clay yields only a small amount of water, and that very slowly. Dug wells are usually most satisfactory where clay is near the surface, but should be carefully covered and protected from pollution.

TILL.

Till is a heterogeneous mixture of clay, sand, gravel, and bowlders. In texture it ranges from very pervious to impervious, according to its content of sand or of clay. In few places is it definitely bedded. Water generally occurs in it in minute, more or less tubular, channels, but occasionally is distributed through interstratified sandy beds. In the finer, more loamy phases the supply is not abundant, but the coarser portions of the material furnish water more plentifully.

In the aggregate, till yields a large amount of water, and where it is sufficiently thick it forms a most convenient and accessible source of supply, but because its material is so irregularly disposed the success of the wells varies greatly. Water is usually found in it close to the surface, but better water can be obtained by casing off these upper water-bearing beds and extending the wells to greater depth. In general, wells of large diameter, similar to those dug in clay, are most satisfactory, for the surface of the till exposed inside the well—that is, the surface from which water can enter the well—is much greater than that exposed in a bored well, and the larger wells also have greater storage capacities. Dug wells may therefore utilize small supplies which would be insufficient for bored wells.

The water of till is generally uncontaminated, because in its downward passage through the clay, of which till is in part composed, it is subjected to thorough filtration. If the water does become polluted, however, it may retain its dangerous character for a long time and for considerable distances.

Till is widely distributed over the northeastern and north-central parts of the United States in the great areas covered by glacial drift. The southern border of the glacial deposits extends from Marthas Vineyard, in Massachusetts, through Long Island and northern New Jersey, across northern Pennsylvania into the southwestern part of New York. Thence it turns southwestward across Pennsylvania and Ohio, southern Indiana, Illinois, and central Missouri, and then swings northwestward into Canada.

SANDSTONE, CONGLOMERATE, AND QUARTZITE.

Sandstone is, on the whole, the best water bearer of the solid rocks. Under the most favorable conditions it is saturated throughout its extent below the ground-water level and yields water freely wherever it is struck by the drill, although some of the fine-grained sandstones yield it less readily. Water derived from sandstone is of better average quality than that obtained from any other material except sand and gravel. It is seldom polluted, and the wells supplying it can generally be safely used if they are cased to keep out surface water. Wells obtaining water from sandstone are usually drilled, although where the sandstone is very near the surface dug wells are common.

In the Appalachian Plateau—the area comprising the bluegrass district of Kentucky, the Nashville basin of Tennessee, and the Cumberland and other plateaus of Tennessee, West Virginia, western Pennsylvania, and New York—sandstone is perhaps the chief of the water-bearing sedimentary rocks. Where sandstone beds are exposed along ravines springs issue from them, and these springs are the source of supply for a large number of the inhabitants.

Porous sandstones also underlie the great plains of the Dakotas, Kansas, and Nebraska, and yield artesian flows throughout an extensive area. Over much of the region that lies farther south they also furnish abundant underground water.

In some places conglomerate yields considerable water, although as a rule its absorptive capacity is not so great as that of sandstone, and it is not so widely distributed.

Quartzite is a metamorphosed sandstone, the spaces between the grains being filled by hard, siliceous matter. Because of this filling of the pores there is little chance for water to enter the rock, hence it is not commonly an important source of water.

Old sandstones, shales, and other sedimentary rocks that have been altered to quartzites or slates lie near the surface in the Appalachian Mountains, the Ozark and Superior highlands, and the Rocky Mountains, and on the borders of these higher lands yield some water, but generally both the occurrence and quality of such water are uncertain.

SHALE.

Shale, like clay, is a poor water bearer, but may yield water from bedding, joint, and cleavage planes, and other crevices. It is most important, however, as a confining layer to prevent the escape of water from porous sandstone that may be interbedded with it. The water in shale is reached by deep wells and is generally uncontaminated by the bacteria of disease, though it may be salty or bitter or otherwise undesirable.

LIMESTONE.

The water of limestone occurs mainly in open channels and caverns which have been formed by the solvent action of water passing along joint or bedding planes. These caverns and water channels are very irregularly distributed and their location can seldom be determined by examining the surface, but most deep wells in limestone regions encounter one or more such passages at relatively slight depth. Adjacent wells sunk in limestone, even if only a few feet apart, may obtain very different results, as a difference of a foot or two in position may mean missing a water channel. The water of limestone regions contains dissolved calcium carbonate (commonly called carbonate of lime) which makes it hard, but usually it is not otherwise heavily mineralized. It is, however, likely to be polluted owing to the fact that much of the water of the underground streams in limestone has found its way downward through sink holes and carries with it more or less surface wash.

Water-bearing limestones occur in the southern and southeastern portions of the United States and also in the Appalachian Mountains, but owing to the poor quality of the water, recourse is usually had to springs or to wells sunk in other rocks.

GRANITE, GNEISS, AND SCHIST.

Granite and gneiss are very dense and have very small pore spaces, and therefore hold but little water. Schist may contain considerable water that has penetrated along foliation planes and is held by the rock, but it gives up water very slowly and is not important as a source of supply. The joints in these rocks yield the largest amounts. Joints are most common near the surface and diminish in number and definiteness with increase in depth. For this reason most wells in crystalline rocks obtain water, if at all, within 200 or 300 feet of the surface, and it is generally useless to go deeper than 500 feet, although in some places, as at Atlanta, Ga., water supplies have been obtained from them at depths as great as 1,600 feet.

The joints in crystalline rocks usually form complex systems of intersecting planes, and polluted water may pass in a zigzag course from the surface downward along the joints until finally it reaches the well at a depth of many hundred feet.

Varieties of the older crystalline rocks outcrop or lie near the surface over the Piedmont area along the eastern front of the Appalachian Mountains, along the Sierra Nevada, and in parts of the Cascade and other ranges of the Pacific coast. In the inhabited districts in these areas some water is obtained from shallow wells sunk into the upper, decayed portion of these rocks, but where surface water is available streams and springs are used for domestic supplies.

LAKE AND STREAM DEPOSITS.

Along the northern portion of the Atlantic coastal plain there are extensive lake and stream deposits of clay, sand, and gravel, which are largely drawn upon for domestic water supply. This water is usually plentiful and good.

In the lower Mississippi Valley the fine silts of the flood-plain deposits are saturated with water a short distance below the surface and furnish abundant supplies to small wells. The chief drawback to shallow wells in this material is the unusually small mesh of the screens that are necessary to exclude the fine sand from the wells. In most places, however, a lens of coarser sand or gravel can be located, and this can be drawn on for water supply without danger of clogging the screen.

In many parts of the arid region of the western United States there are great basins or valleys which are deeply filled with sediments brought down by streams and deposited in former lakes. In some places these unconsolidated sands and silts contain water at shallow depths, and they form the chief source of supply throughout much of the Great Basin region of Utah, Nevada, southeastern Oregon, and southeastern California. In the more favorably situated of these desert valleys, notably in the Coachella Valley, in southeastern California, the deeper water of the unconsolidated deposits may be under sufficient artesian head to yield flowing wells.

In the great central valley of California and in the coastal slopes of the Pacific States there are also deep alluvial deposits that are of great importance as sources of underground water. Those of the coastal plain of southern California have been extensively tapped to obtain water for irrigation, and water is also drawn from similar deposits around Puget Sound.

Many smaller deposits of alluvial material at the bases of the western mountain ranges also yield valuable supplies of water to shallow wells.

OIL AND GAS BEARING FORMATIONS.

STRUCTURE AND CHARACTER.

Oil and gas occur under conditions that here need but brief description. As a rule they are associated with the rock structures called anticlines—upward, archlike folds of the rocks—along the flanks or in the highest portions of which oil and gas collect. Where both are present the gas overlies the oil, which in turn lies upon water-bearing beds. The presence of underlying water is usually considered necessary to the collection of oil, as because of its lesser specific gravity the oil rises above the water, is forced into the highest parts of the

folds, and is held there by the overlying impervious rocks and the underlying water. Anticlinal folding, however, is not an absolutely essential feature, for it is not found in all oil fields.

Oil and gas occur almost entirely in sedimentary rocks (shales and sandstones), and their origin is very generally ascribed to the slow decomposition and distillation of organic matter. Rarely are they found to penetrate from sedimentary into igneous or plutonic rocks.

DISTRIBUTION.

Since the discovery of petroleum in commercial quantities in Pennsylvania the development of the oil fields of the United States has progressed rapidly, and the present oil and gas production of the United States is greater than that of any other country.

Oil and gas are found in the Appalachian field at depths ranging from 400 to 3,000 feet, and are drawn from several horizons. The reservoirs are made up of layers of porous sandstone which are separated by shaly beds. Within the sandstone layers the oil has accumulated in "pools," presumably under the influence of gravity.

The many beds of sandstone form a series of rocks about 2,000 feet thick, deposited during the Devonian and Carboniferous periods of geologic time. Near the western margin of the Appalachian field the oil and gas bearing beds dip gently southward or southeastward, so that the oil-bearing sandstones are carried farther beneath the surface. In West Virginia oil is obtained from wells between 3,000 and 4,000 feet deep.

In that part of the Pennsylvania field which lies within the Appalachian zone of folding, gas and oil are in places found only within the area of the folds. As the gas, on account of its lower specific gravity, lies above the oil, in some localities it is possible to drill wells on the flanks of a fold and reach the oil directly without meeting the gas.

In western Ohio and Indiana oil is produced from the Trenton limestone, a rock different from that found in the Pennsylvania field. The original productive Ohio field has been developed until it now extends across Indiana and into Illinois. The wells of this field range in depth from 100 to 1,400 feet. In eastern Illinois oil is obtained at depths ranging from 400 to 600 feet from soft and very porous limestone lying beneath beds of shale.

In the oil fields of southeastern Kansas and adjacent parts of Oklahoma the oil and gas reservoirs are in sandstone interbedded with shale.[a] As the outcrops of some of the sandstone beds may be traced into shale, and as the records of wells short distances apart differ greatly, it seems probable that the sandstone beds form lenses

[a] Adams, George I., and others, Economic geology of the Iola quadrangle, Kansas; Bull. U. S. Geol. Survey No. 238, 1904, p. 25.

whose position and extent can not be predicted, except within wide limits. The beds also vary exceedingly in their content of oil and gas. The depth of the productive beds increases southward, being 400 to 700 feet in Kansas and more than 1,000 feet in the Osage and Cherokee Nations, Oklahoma.

The Gulf oil fields, which were opened in 1891 by the great Lucas gusher at Beaumont, Tex., and have been extended into a number of other localities in Texas and in Louisiana, are peculiar in that the oil and gas occur chiefly in unconsolidated sands that lie between capping layers of clay, though they are found also in this field in sandstone and in porous limestone. The petroleum at Beaumont is produced from a loose, honey-combed rock, lying 1,000 to 1,200 feet below the surface.

In California oil is found in friable sandstone and shale which are of much more recent geologic age than the productive beds of the eastern fields. Some wells reach depths of 4,000 feet or more. On account of the structure and location of the producing beds some of the wells near the coast are sunk through the shallow water off shore, and near Santa Barbara the oil derricks are erected on long piers and built out into the surf.

In Alaska petroleum fields are being explored on the west shore of Cook Inlet, at Cold Bay on the Alaska Peninsula, and near Controller Bay. The oil in these fields is found in sandy shale whose history is involved with that of overlying or intrusive beds. The structure is complex and developments are yet too meager to permit accurate determination of either the extent or character of the productive beds.

Oil in small quantities is found in several States outside the great fields, notably in Michigan, Colorado, Utah, and Wyoming. In Wyoming the indications give promise of the future production of large quantities of petroleum.

HISTORY OF WELL DRILLING.

ASIA.

In the dry regions of Asia the climate, the universal scarcity of water, the locally dense population, and the dominance of agriculture resulted in an early development of the art of constructing wells. It is not surprising that in China, a country prolific in inventions that are in modern use, there should have been devised, centuries ago, for well drilling, a churn drill which in principle is like the churn drill used to-day. It is also to the early Chinese engineers that we are indebted for one of the few known methods of sinking wells through loose soil and quicksand to great depths; that is, by constructing a curb of stone or brick, which settles as the excavation

is deepened and thereby reduces the pressure of the surrounding material. The ancient writings of the Chinese contain occasional references to well-drilling machines, and to the Chinese also belongs the credit of reducing well drilling to a science. The Chinese, however, though led, naturally enough, to the invention of means of well drilling, especially in the more arid parts of their country, on the boundaries of the great desert of Gobi, reached only a very primitive stage in the mechanical part of the work, and they have made slight improvement in their machinery during the last century, which has witnessed such remarkable mechanical development in the United States.

In western China, near the borders of Thibet, a method of drilling for petroleum in use at the present day illustrates the primitive though scientific manner of well construction in that country. The drilling tool is of the free-falling kind, a hard-wood rod or lifter having an iron cap at each end serving as the hammer or maul. This is fastened to the top of an iron link and falls on the chisel or bit attached to the bottom of the link. (This device is the earliest form of the Canadian pole-tool apparatus used in this country, but as employed in America the wooden rods are used not as a maul but merely as a lifter.) The wear on the parts of the string of tools thus coming into violent contact is very great and necessitates their frequent renewal. The tools are lifted and dropped by means of a windlass having an automatic release. The drill has a narrow horizontal cutting edge by which the rock is spalled off and pounded into bits which may be removed with a sand bucket. The cable is made of twisted strands of rattan. With this outfit a great expenditure of time and labor may be required to produce meager results, and yet by its use wells have been drilled to a depth of 3,600 feet.

EUROPE.

The science of deep-well drilling received great impetus through experience gained in drilling the Passy well of Paris, completed in 1857, which was curbed to a depth of 1,923 feet. Its diameter was $2\frac{1}{3}$ feet and it delivered 5,588,000 gallons of water daily to a height of 54 feet above the surface. Even more remarkable than this is the mammoth well at La Chapelle, which has a diameter of $5\frac{1}{2}$ feet and extends to a depth of more than 1,000 feet. The drill used in constructing this well weighed 4 tons and was operated by a powerful steam engine that caused it to strike 20 blows a minute.

The artesian well at Grenelle, near Paris, completed in 1841, was for many years the deepest well in the world. The history of the seven years of incessant labor expended in its construction has been equalled in interest by that of very few other engineering enterprises.

It was in drilling this well that workmen first learned the requirements of deep drilling and first exercised their ingenuity in recovering broken parts of the drill and rods. A final depth of 1,798 feet was reached, drilling being stopped in a large cavity from which water having a temperature of 82° F. rose with great force to the surface, forming a large flowing artesian well—"a parabolic fountain" many feet in height.

The successful completion of these deep wells in France was followed by deep borings in England and Germany. Many of these were of great dimensions and for the first time gave the geologist an idea of the underground structure of the rocks, nearly every scientific society having investigated the drilling operations from one or another point of view.

UNITED STATES.

EARLY DRILLING.

Drilled and bored wells for water supply have largely superseded dug wells in many parts of the United States, because water obtained from the deeper sources that are tapped by drilled wells is less likely to be contaminated than that obtained near the surface, and the supply of these deeper wells is also usually more constant than that of shallow dug wells.

The methods of drilling water wells have been greatly improved during recent years by experience gained in sinking to great depths for oil and gas, such drilling having resulted in the development of smaller and more efficient tools.

Contemporaneous with the development of the art of deep boring in Europe, deep wells were first put down in the United States at Charleston, S. C., at Louisville, Ky., and at St. Louis, Mo. In the Pennsylvania oil fields wells 2,000 to 4,000 feet deep were drilled, the first deep well in the celebrated Oil Creek region, according to a published account of the early development of the fields,[a] having been drilled by Jonathan Watson in 1866 to a depth of 2,130 feet. With the discovery of oil the well-drilling business became continuous and profitable and soon attracted the attention of engineers whose ingenuity was taxed to the utmost by its obstacles and mishaps. At present it engages the interest of some of the most expert engineers in the country, for, with the extension of artesian-water development to nearly all parts of the world, drillers have encountered nearly every variety of geologic formation, and therefore nearly every kind of difficulty and mishap.

Tubular wells lined with iron pipe or casing superseded wells of larger diameter lined with wooden curbing or conductor pipe. In

[a] McLaurin, J. J., Sketches in crude oil.

the central and western States tubular wells were not commonly used until 1875, but along the Atlantic coast they were drilled much earlier. As early as 1849 tubular wells were drilled with machinery and tools designed by Jesse N. Bolles and a Mr. Knight.

DRIVEN WELLS.

In localities where a pointed pipe can be driven easily to the water level many wells known as "drive" or "driven" wells were put down between 1865 and 1885, and a few such wells are still sunk. Some of these wells are made by pointing the end of a piece of iron pipe, drilling small holes near the pointed part, and driving this pipe into the earth with a sledge or drop hammer. Other sections of pipe are screwed on as the well is driven deeper. In some wells pointed screens made in various ways are attached to the bottom of the pipe thus driven. These screens prevent coarse sand from entering the pipe and wearing out the pipe valves, but many wells of this kind are short lived, and in some localities tubular wells of larger diameter, made by other methods, have taken their place.

Driven wells can not be put down in rock and many difficulties are met in sinking them. In order that they may be successful, it is necessary that the perforated end of the pipe be driven into a good water-bearing stratum in sand or gravel within 30 feet of the surface and there stopped. A patent was granted on the drive well to a Mr. Green after the civil war, but drive wells had been put down as early as 1861.

WELL AUGERS.

The method of boring wells by turning an auger into the earth was in common use throughout the country between 1865 and 1885 and is still employed in some sections. One of the first augers used for this purpose was made by J. J. W. Adams in Virginia in 1855 and is now in the possession of George D. Loomis, of Tiffin, Ohio, from whom many historical data were obtained.

Well augers, ranging in diameter from 2 to 4 inches, were much used through the Central and Western States during their settlement, and in some parts of the country they are still used, though in most places the open bored well, lined with wooden plank or with sewer pipe, has been superseded by the tubular well made by sinking a wrought-iron pipe into the earth.

JETTING METHOD.

A jetting outfit for use in sinking wells in unconsolidated deposits was built in 1884 by W. C. Wells, who did much to demonstrate its utility. In using this device the material is loosened by a strong

current of water directed through a suitable nozzle or bit and is carried to the surface and thus removed by the return stream of water. Where it can be used, it is a very rapid, efficient, and cheap means of sinking wells.

SELF-CLEANING METHOD.

Machinery and tools for drilling tubular wells by what is now known as the "self-cleaning" method were constructed and used in 1857 or shortly before by Jesse N. Bolles. This method is often called "hydraulic," but the material is loosened and broken up by the percussion of a drill bit. Water, however, provides continuous self-cleaning of the hole, for by the action of the drill the loosened material is pumped up through the hollow drill rods and delivered at the surface.

Following Mr. Bolles in the use of tools of this kind came Jesse Button, a well driller and inventor. Soon after the discovery of oil in northwestern Pennsylvania Mr. Button did much drilling with a machine especially constructed for the use of the self-cleaning tools, and aided greatly in making this method of drilling efficient.

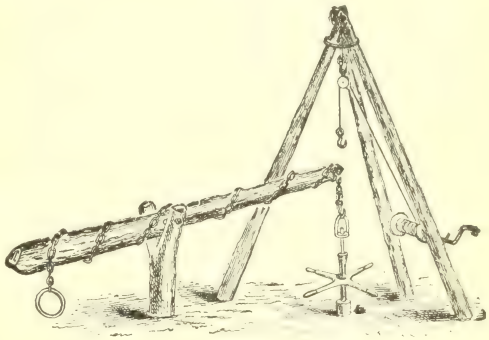


FIGURE. 4.—Spring-pole drilling outfit.

SPRING-POLE OR CHURN DRILL.

The first churn drill employed in the United States was a crudely constructed device (fig. 4) consisting of a small tree or spring pole, sufficiently strong to bear the weight of rope and drill, supported in a forked upright and securely fastened down at the larger end or weighted so as to counterbalance the drill. The pole was inclined over the hole at an angle of 15° to 30° or more from the horizontal, so that the tools could be raised and lowered in the well. The tools, which were generally made by local blacksmiths, consisted of solid wooden rods, seven-eighths inch to 1½ inches in diameter, fitted with box-and-pin joints and attached to the spring pole by a rope or chain. The cutting instrument was a steel chisel or drill welded to an iron stem a few feet long and attached to the lower end of the line of rods. Cross handles were bolted to the rods, which were supported by a swivel, and by these the drill was slowly turned during the drilling. The derrick consisted of three timbers, 20 to 30 feet or more in height, bolted together at the top; the joint was strengthened by an iron circle slipped over the timbers.

The machine was operated by two to four men, who by their weight brought the pole down quickly, so that the drill would strike a blow on the bottom of the hole. It was then lifted again by the spring of the pole. When it became necessary to pump out the accumulated drillings the tools were raised by means of a rope passed through a pulley at the head of the derrick and carried to a windlass supported on a crank shaft between two of the legs. After the hole had been cleaned, the tools were lowered by the same device. In raising the drill the different sections were unscrewed piece by piece as they came up, and they were screwed together again when the drill was lowered. A clip on the end of the rope from the windlass could be inserted in the swivel at the upper end of the string of tools, thus enabling the driller to suspend the tools temporarily when the deepening of the hole necessitated lengthening the rope or chain fastened to the spring pole. The sand pump was a long tube, 3 inches in diameter, with a hinged bottom opening inward and a piston valve working on a sliding rod, somewhat in the manner of a syringe. It was lowered to the bottom, and when the poles, which were attached to the sliding rod of the pump, were raised quickly the drillings were sucked into the pump by the sliding valve, retained by the bottom valve, and thus pumped out.

Sometimes the tools were operated by a number of men perched on a scaffold built about the well. The spring of the pole would lift the tools for the blow and the weight of the men bring them down. The work was extremely laborious, the speed attained being about 2 feet a day for each man stationed on the scaffold. The men had to rest every few minutes, and if it was desired to drill continuously it was necessary to supply double sets of men, who relieved each other after a few minutes' work. The method was often called "kicking down a well," and was employed in sinking hundred of shallow wells. It afforded men of limited means a way of obtaining a water supply, but was inadequate for deep-well drilling, and has become nearly obsolete. In drilling hard material progress was extremely slow; the force of the blow decreased as soon as a few inches had been drilled, for the drill must recut the drillings, so that the tools had to be hoisted out and the hole sand-pumped frequently.

The wells sunk by this process were as a rule not more than 4 inches in diameter and were comparatively shallow, for their depth was determined by the elasticity or counterweight of the pole and the ability of the operators to raise the tools out of the well when it became necessary to remove the drillings. However, some of them exceeded 300 feet in depth.

STANDARD METHOD.

The sinking of deep water wells and of deep borings for gas and oil made necessary the use of heavier tools, differing from those of

the spring-pole outfit. The first step in the evolution of the spring pole into the standard method was the substitution of horse power for manual labor in working the tools. The next improvement was the replacement of the spring pole by the walking beam, whose motion depends not on elasticity but on power transmitted from an engine through a jack wheel and crank shaft. The first oil well drilled by steam power was put down opposite Tidioute, Pa., in 1860.

The most important implements of modern drilling are the "jars," which were long ago invented by William Morris. They consist of two linked pieces of steel of good quality, having an endwise motion, or slack, of 6 to 9 inches. They enable the delivery of a quick, hard, upward blow, which jars the tools free when the drill is working in caving or creviced material. For "fishing" for lost tools they are made longer to enable a harder blow to be delivered. Their invention made possible the drilling of much deeper holes than had before been attempted, for the driller knew that if the tools became stuck he need not depend on mere strength of rope in withdrawing them. A quick upward stroke with good, heavy, well-made jars will exert a greater force on the drill than a steady pull of several tons. It is reported that George Smith, of Rouseville, forged the first steel-lined jars in 1866, for H. Leo Nelson,[a] who also in that year adopted the "Pleasantville rig," discarding the "grasshopper." In the former the walking beam is fastened in the center to the "samson post," with one end attached to the rods in the well and the other to the band-wheel crank.

Many improvements on pumping rigs, drilling tools, and gas rigs were patented by George Koch, of East Sandy, Pa. A line to control the engine from the derrick was first used by Samuel Taft, in 1867, in drilling a well near McClintockville; and a device to regulate the motion of the engine by means of a rod from the derrick attached to the throttle valve of the engine was first used by Henry Webber, who drilled a 600-foot well near Smoky City in 1863. Webber also, perhaps for the first time, dressed the tools in a forge under the derrick.

To exclude surface water a leather "seed bag," filled with flaxseed, was tied firmly around the pump tubing and let down to the proper depth. In a few hours the seed swelled and filled the space between the tubing and the wall of the well and rendered it impervious to the passage of water.

Drilling "wet holes" was slow and uncertain, as the tools were likely to break, and whether or not a well would be successful could not be known until the pump exhausted the water; but more than 5,000 wells were sunk with the rude appliances in use up to 1868,

[a] McLaurin, J. J., Sketches in crude oil.

before the water was shut out by inserting a larger pipe—a casing—which was usually carried to the top of the first sand. The use of casing was the greatest improvement ever devised in drilling for oil, and holes can now be sunk safely and rapidly to a depth of 5,000 feet.

HYDRAULIC ROTARY METHOD.

Although rotary methods of drilling had been used for a number of years previous to the opening of the Spindle Top oil field in Texas, the remarkable success of the hydraulic rotary drill in that field in 1901 gave great impetus to its improvement and its more general use. Its work is accomplished by means of a cutting shoe on the bottom of the casing, the whole string of casing being rotated by a suitable device. As fast as the material is loosened it is carried to the surface by a powerful water current that is forced down the inside of the pipe to the cutting shoe and thence escapes upward between the casing and wall of the hole. In the early days of rotary drilling a second casing was sunk closely following the cutting shoe, but about 1890 it was found that thick mud used with the drill water puddled and plastered up the walls of the hole and was nearly as efficient as second casing.

The method is adapted for use only in unconsolidated materials and in soft friable rocks with small crevices and pores which can be sufficiently plastered with mud to prevent too great a loss of drill water.

CORE DRILLS.

In drilling prospect holes for coal or for metallic or other deposits, or to determine the suitability of the underlying formations for bridge or other structural foundations, it is very desirable to obtain intact samples of the materials penetrated. Core drills are extensively used for this purpose, and they have been developed to a high degree of efficiency. As in the hydraulic rotary method, core drilling is accomplished by an annular shoe or bit set on the lower end of a string of hollow rods; but core drills are adapted to penetrating even the hardest rock, and instead of grinding all the material to a slush or mud, they remove the central part of the hole as a solid core.

Though core drills are seldom used directly for drilling water or oil wells, adaptations of the core-drill principle are sometimes used with well-drilling outfits. (See pp. 78–88.)

DISTRIBUTION OF DRILLED WELLS.

Drilled wells are in use in most parts of the world reached by ordinary trade routes and even in areas beyond the main lines of travel. In the United States they are most common in localities where flowing

artesian water is to be reached at considerable depths, as in North and South Dakota, the Atlantic coastal plain, and southern California; in areas where relatively deep wells are required for pure but non-flowing water, as in nearly all of the eastern States; and in localities where oil and gas exist, as in Pennsylvania, West Virginia, Ohio, Indiana, Texas, Oklahoma, Colorado, Wyoming, and California. In South America they are used in developing the water resources of desert Peru and Chile, from Callao to Valparaiso, where artesian wells furnish some of the municipal and agricultural water supplies. In Siberia portable drilling rigs have been taken to the frozen flood plains of the northern rivers for gold prospecting. By the enterprise of American supply houses and drilling firms portable outfits have been taken to the arid portions of Greece, Italy, and Spain, to China and Japan, to the oil districts of Sumatra and Rangoon, to the deserts of Algeria and Egypt, to Australia, and to nearly every port of call in South Africa. In the country last named well drilling is encouraged and aided by the Cape government in utilizing underground water supplies for stock and for agricultural industries. The cost of the wells is so great that the landowner is unable to bear it alone, and the government therefore assists him by supplying machinery, material, and skilled labor, while the farmer furnishes transportation and Kaffir labor.[a] Since the value of a farm is very greatly increased by an ample water supply, the government of late has required the farmer to pay a much greater share of the cost of sinking a well.

In order to show the wide distribution of deep wells and the great depths to which they have been sunk the following list of 30 deep borings in various parts of the world has been compiled. There are, of course, many other borings that compare favorably with these in depth, but those listed are illustrative.

List of deep-well borings.

[Data collected by B. L. Johnson.]

Location.	Depth.	Diameter.	Object.	Remarks.
	Feet.	*Inches.*		
East of Rybnick, Upper Silesia, Germany.	6,572	3.6 to 2.7	Coal.....	Cost $18,241. Completed Aug., 1893, after 1½ years' work. Deepest bore in the world.
Schladeback, near Leipsic, Germany.	5,735	11 to 1.3	Coal.....	Cost $53,076. Completed about 1893. Average daily rate of drilling, 4½ feet.
Knurow, Upper Silesia.....	4,173	192 to 13	.....	
Springs, 25 miles east of Johannesburg, South Africa.	5,582	2 to 1⅜	.....	Completed 1905, after 9 months' work. Diamond drill hole.
Dornkloof, 16 miles east of Randfontein, South Africa.	5,560	2 to 1⅜	.....	Completed December, 1904, after 14 months' actual work. Diamond drill hole.
Randfontein, South Africa...	5,002	.....	.....	Diamond drill hole.
Turfontein Estates, Johannesburg, South Africa.	4,845	.....	.....	Do.

[a] Ritso, Bernard W., The artesian wells of the Cape Colony: Rept. South African Assoc. Adv. Sci., vol. 1, 1893, pp. 1–21.

List of deep-well borings—Continued.

Location.	Depth.	Diameter.	Object.	Remarks.
	Feet.	*Inches.*		
Near Boksberg on the Rand, South Africa.	4,800			
Clerksberg district, South Africa.	4,500			
In the Vlakfontein district, South Africa.	4,003			
In the Black Reed series, 12 miles south of the Main Reef series on the Rand.	4,500			Diamond drill hole.
2½ miles west of West Elizabeth, Pa.	5,575	10 to 6¼	Oil	Cost $40,000. Deepest well drilled with a cable; deepest well in the United States; third deepest well in the world.
In Aleppo Township, Greene County, Pa.	5,322	13 to 6⅝	Gas	Abandoned July, 1905.
Pittsburg, Pa.	4,618		Oil or gas	
4 miles southeast of Wheeling, W. Va.	4,500	4⅞	do	
In the city of Erie, Pa.	4,460		do	Abandoned 1889.
Irwin, Westmoreland County, Pa.	4,380		do	
Buchanan well, 6½ miles south of Burgettstown, Pa.	4,303		do	
Northampton, Mass.	4,022		Water	
New Haven Conn.	4,000	8	do	
Renovo, Pa.	4,000		Oil	
Bimerah Run, Queensland	5,045		Water	Flow, 70,000 gallons a day.
Elderslie, No. 2, Queensland.	4,523		do	Flow, 1,600,000 gallons a day; temperature 202° F.
Bimerah, Queensland	4,860			
Glenariffe, Queensland	4,140			
Warbreccan, Queensland	4,125			
Winton, Queensland	4,010			
Darr River Downs, No. 4, Queensland.	4,000			
Dolgelly bore, New South Wales.	4,086		do	Flow, 745,200 gallons a day.
One well in state of South Australia.	4,420		do	Flow, 600,000 gallons a day.

METHODS OF WELL DRILLING.

CLASSIFICATION.

Modern well-drilling methods may be grouped into three general classes—percussion, hydraulic, and abrasion methods.

The percussion outfits use a heavy drill bar or other tool, with suitable apparatus for lifting it and allowing it to drop, to pound the rock into fragments small enough to be readily removed from the hole. The percussion principle is utilized in the standard, portable, pole-tool, self-cleaning, and California methods, whose outfits are recognized as distinct but differ in their arrangements for handling the tools rather than in the operation of drilling. The California method belongs in this class, for though its successful use depends on a plentiful supply of water, it involves drilling by percussion.

The hydraulic outfits use water under pressure to loosen the material and bring it to the surface. The chief method in which water plays an active part in drilling—the hydraulic rotary method—has been developed mainly within the last ten years as a result of the discovery of oil in Texas in unconsolidated materials, for penetrating which the hydraulic rotary drill is especially adapted. In the jetting

method used for sinking water wells in unconsolidated deposits water under pressure plays an even more important part than it does in the hydraulic rotary method, for the water jet receives little aid from the drill in loosening the material to be removed.

In methods involving abrasion the rock is worn and chipped off by rotating upon it a shoe or bit armed with some harder material. The abrasion principle is employed by three types of drills, which differ chiefly in the abrasive with which the bit is armed and are known as the diamond, calyx, and the chilled shot drills.

Several methods, including boring, punching, and driving, as well as digging, which do not come within the above classification, are employed to obtain shallow water supplies.

In many wells a single method is not employed throughout the entire work, and in some wells modifications of several methods are successively used. Though percussion tools are usually employed in drilling by any of the percussion methods, the shape of the bit used and the means of removing the drillings may be changed at different stages of progress. In the hydraulic rotary outfit a percussion drill may be substituted for the cutting shoe in penetrating hard strata, and for this purpose chilled shot, or adamantine, is also occasionally used with a suitable revolving shoe. Combinations of the hydraulic rotary and the jetting methods are also employed when penetrating alternate beds of clay and gravel. In the abrasive methods it is often found advantageous in passing through hard or tough material to replace the usual bit by one operated by percussion.

Abrasive or core drills are seldom exclusively employed for well sinking, their particular field of usefulness being in boring prospect holes for ore deposits or for other exploration work.

The terminology employed by well drillers throughout the country is fairly uniform. This uniformity has been brought about through the uniformity of the terms used in catalogues of supply houses and through the migration of drillers from the oil fields of Pennsylvania and West Virginia to other parts of the country. One of the major terms that may be mentioned is the word "rig." Among standard drillers this is usually applied only to the derrick, wheels, and reels, the word "outfit" being used to include the rig, power machinery, tools, and accessories. Those using portable drilling machines, however, apply the term "rig" to the complete machine.

SELECTION OF OUTFIT.

The proper selection of a drilling outfit requires the careful consideration of many factors, chief among which are the location and purpose of the well and the geologic structure of the rocks to be penetrated. In many localities, for example, small tubular wells,

ranging in diameter from 2 to 4 inches and in depth from 50 to 200 feet, will provide satisfactory water supplies; in other localities such wells are not satisfactory and wells of larger diameter are required. The advantage of knowing the kind of outfit to select can readily be understood.

The preference of the driller must also receive consideration. An inexperienced man may quickly be taught to manipulate and use to advantage a new-style rig which a so-called experienced man, strongly prejudiced in favor of the rig with which he is acquainted can not be induced to use carefully and intelligently. This personal factor the well owner or contractor can not ignore; but the man who condemns other well-drilling methods simply because he has found satisfactory in certain localities the one or two methods with which he is acquainted must be set down as an inexperienced or an unintelligent driller.

It must be borne in mind that no one method of drilling is best under all conditions. No one method can even be said to be best under most conditions. Different methods are adapted to different localities; each style of outfit has advantages and disadvantages which must be considered before drilling is begun. The auger, elsewhere obsolete, is still used in many localities, as it is adapted to drilling shallow wells in places where a larger and more expensive rig can not be profitably employed.

STANDARD METHOD.

CHARACTER AND USES.

The largest and deepest wells put down are those sunk to obtain oil, and the heavy standard outfit, now so extensively used, acquired its essential characteristics in the development of the oil industry in Pennsylvania. In overcoming the difficulties encountered in drilling deep holes the tools have been enlarged and the several parts of the outfit have been modified and improved until the size and weight of the tools and the ease with which they are handled surprise those unfamiliar with this class of machinery.

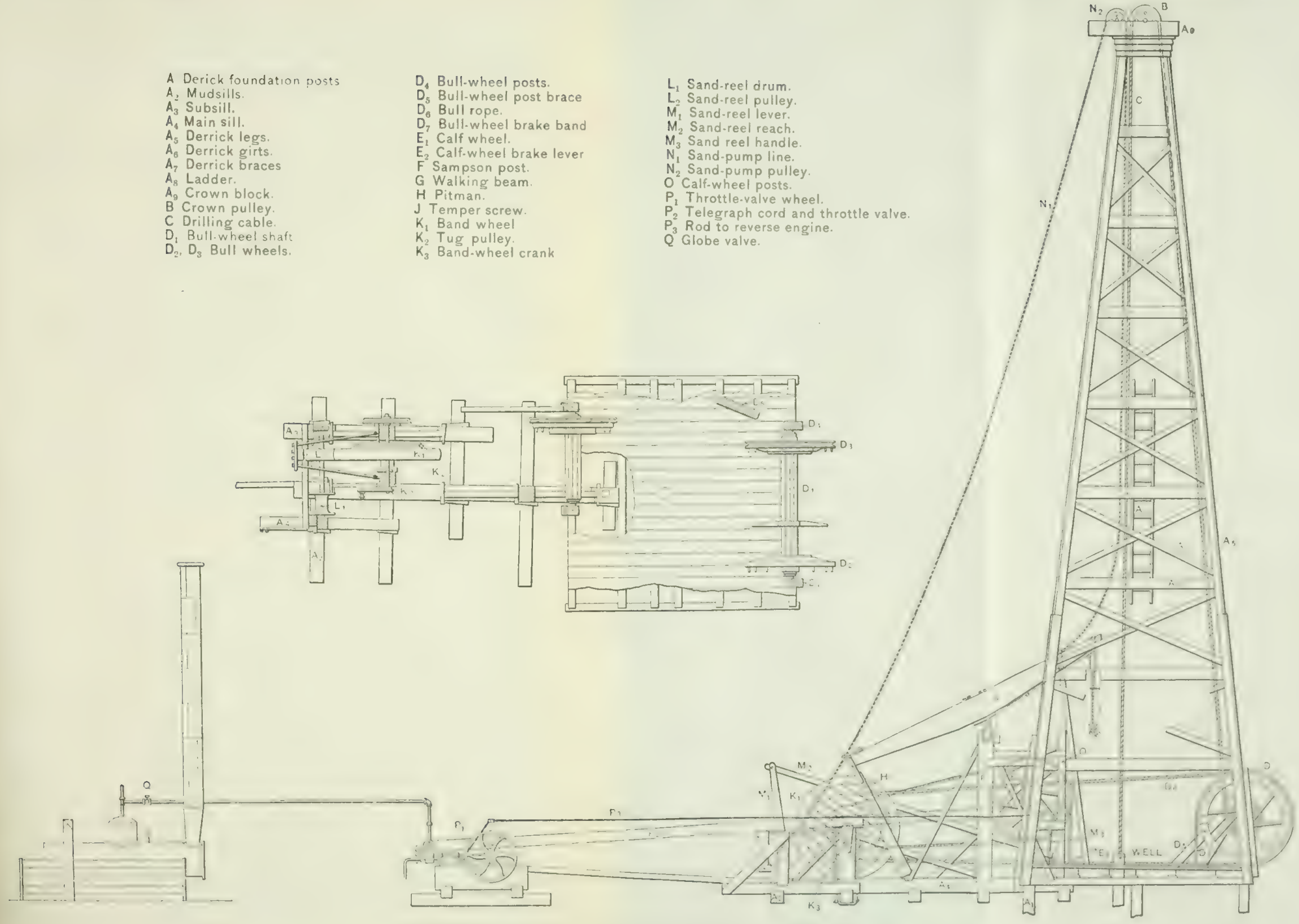
Standard outfits differ little in essential features, but hardly two can be found alike in every detail; the slight variations that exist are due not to some fancy or whim of the driller, but to the need for adapting the outfit to special conditions.

OUTFIT.

RIG.

The most noticeable part of a standard outfit is the derrick, a pyramidal framework, 30 to 90 feet high, erected over the well. In

A Derick foundation posts
A_2 Mudsills.
A_3 Subsill.
A_4 Main sill.
A_5 Derrick legs.
A_6 Derrick girts.
A_7 Derrick braces
A_8 Ladder.
A_9 Crown block.
B Crown pulley.
C Drilling cable.
D_1 Bull-wheel shaft
D_2, D_3 Bull wheels.
D_4 Bull-wheel posts.
D_5 Bull-wheel post brace
D_6 Bull rope.
D_7 Bull-wheel brake band
E_1 Calf wheel.
E_2 Calf-wheel brake lever
F Sampson post.
G Walking beam.
H Pitman.
J Temper screw.
K_1 Band wheel
K_2 Tug pulley.
K_3 Band-wheel crank
L_1 Sand-reel drum.
L_2 Sand-reel pulley.
M_1 Sand-reel lever.
M_2 Sand-reel reach.
M_3 Sand reel handle.
N_1 Sand-pump line.
N_2 Sand-pump pulley.
O Calf-wheel posts.
P_1 Throttle-valve wheel.
P_2 Telegraph cord and throttle valve.
P_3 Rod to reverse engine.
Q Globe valve.



STANDARD DRILLING OUTFIT, COUPLED FOR RAISING TOOLS.

summer the derrick is usually left open except on one side, which is boarded in to form a shed for storing tools and workmen's clothes and to protect the forge—a part of the outfit that is in more or less constant use. In winter the lower part of the derrick is temporarily closed to protect the workmen. In a new territory drillers sometimes close the derrick, even in summer, to keep the results of the drilling secret.

The derrick (Pl. I) consists of four legs, steadied by girts and braces and surmounted by a crown block. In this block is set the crown pulley over which the drilling cable passes. A ladder extending up one side of the derrick provides access to the crown block. The weight of the derrick rests on foundation posts, which are set deep in the ground to render the structure firm.

At one side of the derrick are the bull wheels. This part of the rig consists of a reel, on which the drilling cable is wound, at each end of which is a wheel, usually built up of wooden arms and segments, fastened together with wooden pins. These parts are known to the trade as arms, cants, and handles. The whole is set firmly into the bull-wheel posts and strengthened by the bull-wheel post brace. The wheel at the farther end of the reel in the illustration (Pl. I, D_3) is grooved to receive the bull rope, which acts as a belt to operate the reel. The brake by which the reel is controlled passes over the near wheel of the illustration and is controlled by a lever. In the early rigs this brake consisted of rope or a piece of old rubber belting. When the tools were lowered the rope would burn and smoke, and the rubber would emit a very disagreeable odor. In present rigs an iron brake band is used.

In the California style of standard rig a second reel, known as the calf wheel, is placed on the side of the derrick opposite the bull wheels. It carries a cable that is used in lowering and in pulling casing. It is claimed that in deep drilling it saves much time as it obviates the necessity of disconnecting the tools from the drilling cable for these operations.

Opposite the bull wheels is the samson post, usually about 14 feet long. This post is strongly braced and supports the walking beam. The derrick end of this beam is directly over the well and carries the temper screw to which the tools are fastened and by which they are fed downward. The other end of the beam carries a pitman, which is connected with the crank of the jack or band wheel by a wrist pin. This band wheel is supported on jack posts and transmits power to the several parts of the rig—to the walking beam by means of crank and pitman, and to the bull wheels through the tug wheel and bull rope. In the California rig the calf wheel is also operated by the band wheel through a second tug wheel and rope belt. The operation of the calf wheel is usually controlled by a lever and clutch,

and the bull wheels are usually thrown in or out of gear by putting on or removing the bull rope.

The sand reel is just behind the band wheel and is operated by the latter through a friction pulley. This reel is mounted on a knuckle post and is controlled from within the derrick by means of the sand-line pulley, and, as its name indicates, it is used in handling the sand bucket or bailer.

The part of the rig that extends beyond the derrick rests on mud sills, which are usually sunk in trenches and have gains cut in them to receive the subsills and main sill, and the whole foundation is carefully leveled up and firmly keyed together.

The headache post, also called the life-preserver, is a comparatively recent improvement. As its name implies, its purpose is to save the driller from injury to the head if the wrist pin breaks or the pitman is thrown out of adjustment while drilling, as it prevents the derrick end of the walking beam from dropping and injuring anyone who may be beneath it. This post is usually a piece of heavy timber set on the main sill directly under the walking beam, so that in case of accident the walking beam can fall only a few inches. It is also useful when repairs are necessary to the pitman or the band wheel and crank, for a block may then be placed between the headache post and the walking beam, and the pitman relieved of its weight and slipped from the wrist pin without making it necessary to disconnect the tools from the temper screw.

Variations in the size of the parts of a rig depend on the amount and difficulty of the work to be performed. At Bradford, Pa., where few of the oil wells are more than 2,000 feet deep, the derricks are 72 feet in height; at Kittanning, where wells between 2,000 and 3,000 feet deep are common, the derricks are 82 feet high. An increase in the length and weight of the tools used is always accompanied by an increase in the size and strength of the derrick. The stems alone of the drills used at Kittanning are 39 to 42 feet long, and the sand buckets used with some outfits are 60 feet long. The walking beam used in this field is also larger than usual, being 24 feet long as compared with 16 feet at Bradford. At Kittanning the hemp drill rope is $2\frac{1}{4}$ inches in diameter; in the Bradford field it is $1\frac{1}{4}$ to $1\frac{1}{2}$ inches. These figures show the structural changes that follow a change in the amount of work to be done.

For a 72-foot derrick about 13,000 board feet of lumber are required for the framework and wheels, and, if the derrick is closed in, about 3,000 feet of siding. In places where it is difficult to get skilled rig builders, as in the Philippines or in newly developed oil regions, bolted wood derricks are very serviceable. The timbers are all framed and distinctly marked, so that the derrick can be easily erected.

Steel derricks have not found much favor, though they are easily taken down, transported, and set up again, and offer slight resistance to the wind. The driller objects to them chiefly because of the delay and expense entailed by the necessity of sending to the supply house for repairs when a part becomes broken or twisted, whereas repairs on wooden derricks can be made quickly by unskilled labor and with cheap material. The loosening of bolts—a serious defect of the steel derrick—has been overcome, at the expense of considerable additional time in erection, by using a guard nut on each bolt.

A bolted wood or steel derrick may be set up in two or three days. Three or four skilled workmen can set up an ordinary nailed derrick in from three to five days, the time depending on the size of the rig and the quality and accessibility of the lumber; but after a nailed derrick has been used for two or three jobs it becomes too badly worn and racked to be set up again.

Where oil wells are drilled close together, or where, on account of trees or buildings, there is limited space for operation, a rig with a short walking beam is sometimes used. This rig occupies a plot about 20 by 50 feet in size, and is very compact and serviceable.

ENGINE AND BOILER.

Beyond the derrick and other parts of the rig is the engine, which furnishes power to the band wheel by a belt. Steam power is almost universally used and is supplied by a boiler placed a short distance from the engine. The throttle of the engine is controlled from the derrick by a double line of telegraph wire passing over small pulley wheels, and the reverse lever is operated by a rod that extends from the engine into the derrick.

A good engine and boiler are just as essential as a good drilling machine, and these parts of the outfit should be selected very carefully. The boiler used in connection with the standard rig ranges from 15 to 40 horsepower and the engine from 12 to 30 horsepower. Boilers are of two general types—horizontal and upright. The horizontal—called the oil-country boiler (see Pl. I, Q)—is in most general use. The upright boiler differs from the horizontal mainly in shape, but is smaller than the oil-country boiler, and is more easily moved and set up. It is used in some parts of the California fields, where it is closed in with natural adobe instead of brick. In many oil and gas fields either oil or gas may be obtained from other wells for fuel under the boiler.

Engines of various styles are used even in the same locality, but all are usually so fitted that they can be controlled from the derrick and are otherwise adapted to the particular needs of the work.

Water for the boiler and for use around the well may be obtained from a near-by water well or from a neighboring stream. If the

source of supply is not too distant, a hose or pipe is led to the outfit and water is drawn by a steam pump, but if the distance is considerable the steam pump is put near the well or stream and water is forced up to a storage tank at the place where drilling is to be done. Steam may be supplied to the pump through insulated pipe led from the boiler, or a gasoline engine may be set up near the pump. Gasoline engines are used with many outfits in Indiana and Pennsylvania and are said to be more economical and to require less care than steam.

Where there is no near-by well or stream from which a water supply can be obtained, a water well is sunk by means of the outfit before work on the oil well can be begun. The water well is usually put down immediately beneath the walking beam, about 3 feet back from the point where the deep hole will be drilled, in order to lessen the labor of drilling it and of pumping the required water. Water for drilling this well and for the boiler is hauled from the nearest available source. After a water supply has been obtained, a pump is so installed that it can be connected with the walking beam, by which it is operated when water is needed.

In the vicinity of Bradford, Pa., water is obtained from wells about 60 feet deep in the valleys and 200 to 300 feet deep in the hills. The cost of sinking water wells adds considerably to the expense of putting down oil wells.

TOOLS.

The string of tools used in deep drilling consists of several parts, all of which have certain definite functions and are the outgrowth of years of experience. A full string (fig. 5, *A*) comprises rope socket, sinker bar, jars, auger stem, and bit. Whether or not the complete string is used depends on the conditions under which drilling is done.

The socket may be fastened to the drilling rope in several ways. It may have a tapered hole in which the rope is secured by knotting; the rope and socket may be riveted together, or the rope may be threaded back and forth through several holes in the socket and secured by wedging.

The sinker bar is a long, heavy bar, which is used to add weight and length and thus aids in keeping the hole straight. It was formerly thought to be an essential part of the string, but it is now seldom used unless a wet hole (one partly filled with water) is being drilled. It then assists in sinking the cable rapidly. If it is placed between the jars and the bit, it adds force to the blows of the latter.

The jars, as previously stated, consist of a pair of linked steel bars. When drilling in rocks in which the bit is apt to stick they are necessary to "jar" the drill loose. The drill responds to the powerful upward blow of the jars as they are jerked violently together by the

stroke of the walking beam when it will not yield to the slow and relatively steady pull of the rope. In ordinary brittle rock the jars are now almost universally discarded, but they have a very important use in "fishing" for lost tools; those intended for this purpose are made longer than jars used in ordinary drilling.

The jars in no sense act as a maul to drive the drill into the rock, as many people suppose. In fact, a good driller so adjusts the cable that it is impossible for the upper jar to strike the lower one except when the cable is raised. The only weight which adds effectiveness to the blow of the drill is the weight of the lower jar, the auger stem, and the drill. The weight of these three parts, or of the two last-named parts, makes up three-fourths to seven-eighths of the total weight of the string of tools. This weight, falling through a distance of several feet, is all that the drill can bear. Some inexperienced drill men give the drill too much rope, so that the bottom of the upper jar strikes into the bottom of the slot of the lower jar at each downward stroke, and in a short time the links are seriously damaged. The stroke must be carefully adjusted to the play of the jars, taking into account the stretching of the rope.

The auger stem gives additional weight to the blows that are struck, and also, by increas-

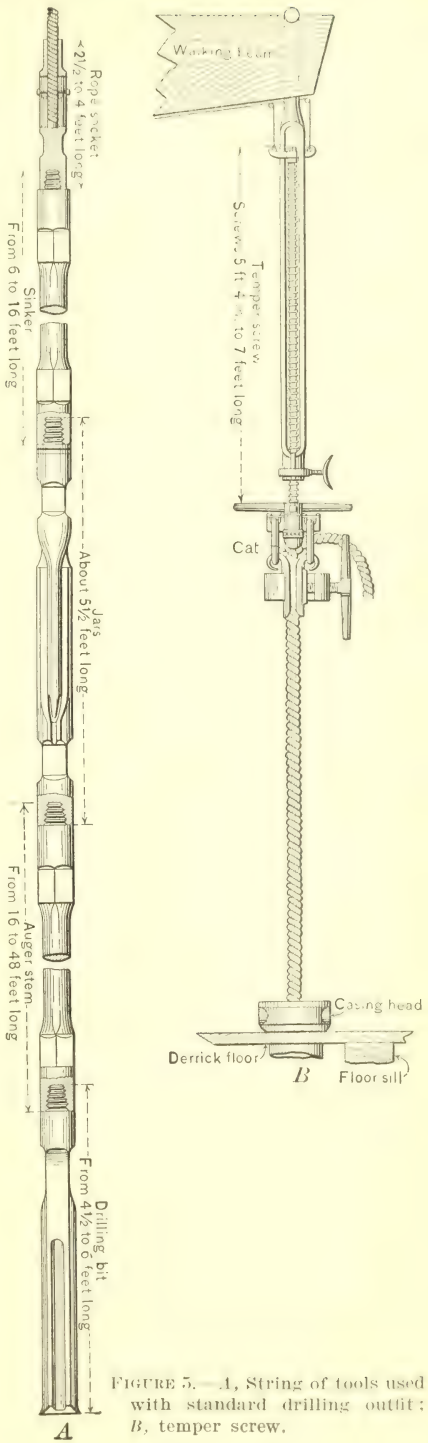


FIGURE 5. A, String of tools used with standard drilling outfit; B, temper screw.

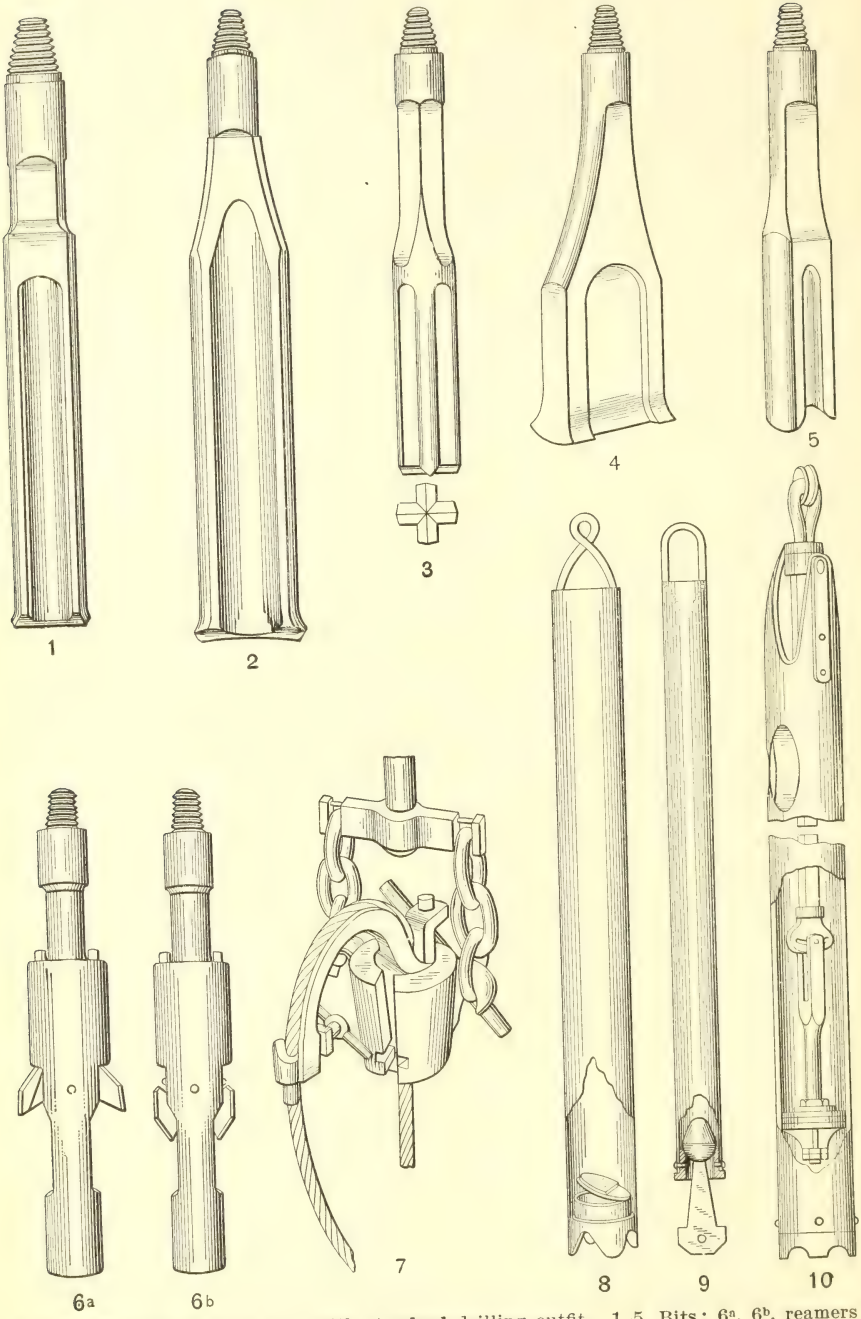


FIGURE 6.—Drilling tools used with standard drilling outfit. 1–5, Bits; 6a, 6b, reamers; 7, rope clamp; 8, 9, sand bailers; 10, sand pump.

ing the length of the drill, helps to maintain a straight hole. It is of the same shape as the sinker bar, but is considerably shorter.

Various patterns of drilling bit are used, according to the character of the rock that is being penetrated. The shape illustrated at the bottom of the string of tools in figure 5, *A*, is used in moderately hard rock; the "Mother Hubbard" pattern (fig. 6^1) is a similar, but thicker, drill that is used in hard, fissured rock; the California pattern (fig. 6^2), which is concave on the bottom, is much used in the shales of the oil districts in that State. A shorter, lighter bit (fig. 6^3) is used in "spudding" at the beginning of drilling. Star bits (fig. 6^4) are sometimes used in creviced rock that dips steeply, and more complex shapes are used in reaming and in other special operations.

All joints of the string of tools have taper screws, so that only a few turns are required to fasten them together. They are screwed up tightly by heavy wrenches on which great leverage is exerted by means of a ratchet floor circle and jack (fig. 7, *A*), or by a simpler arrangement (fig. 7, *B*) in which the floor circle is an arc of band iron with holes punched in it every 2 or 3 inches. These holes give footing to a bar by which the upper wrench is forced around. The great stress that is thus brought on the screw joints binds the string of tools together. When first assembled and screwed together tightly each joint of the string may be marked by a cold chisel cut that extends across it, and each time a joint is put together care is taken to see that it is screwed up as far as or a little farther than it was before. If the two halves of the chisel mark fall short of coinciding, sand or mud in the threads may be the cause, and if this material is not removed and the joint screwed together tightly, the sand may work out, leave the joint loose, and cause loss of all tools below the joint.

TEMPER SCREW.

The cable supporting the string of tools is connected to the walking beam by a temper screw (fig. 5, *B*), which allows the drill to be fed downward as the drill hole is deepened. The temper screw consists of a frame or reins, at whose lower end is a split nut held together by a yoke clamp. Through this nut the main screw passes, and to its lower end is fastened a handle, by which it is turned. Below the handle is attached a ball-bearing swivel, from which depend the clamp links and rope clamps. The cable is gripped tightly between the rope clamps by a C clamp and is prevented from slipping by means of a "cat," made of strands of raveled rope or strips of coarse cloth, loosely plaited or twisted so as to form a cord about as thick as a man's finger in the middle, and tapering toward each end. The "cat" is wound about the cable at the point where the clamps are attached, and the set screw is then turned so as to bring the rope clamps firmly against it.

Slightly different forms of clamp (fig. 6[7]) are sometimes used with wire rope.

When the screw has been run out its full length, and it is desired to bring it up again, the slack of the drilling rope is taken up on the bull-wheel shaft, the pitman of the walking beam is disconnected, and the C clamp is loosened. The yoke clamp is then loosened, the main screw is drawn up through the split nut, the yoke clamp is again tightened, and the temper screw clamped to the cable. Small

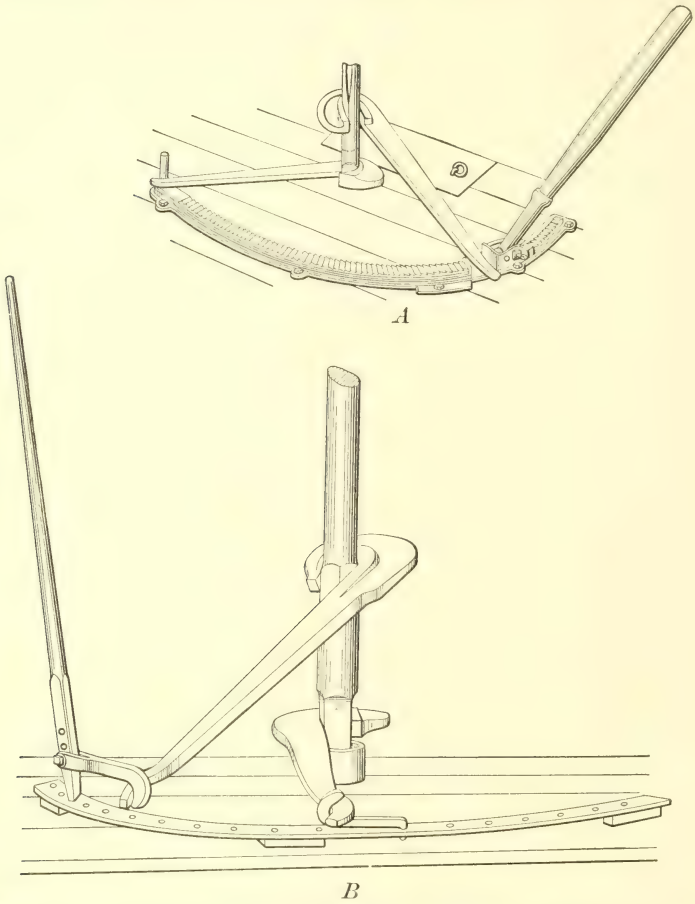


FIGURE 7.—Floor circles: *A*, Rachet and jack; *B*, bar and perforated arc.

ropes are fastened to the short crossbar, or elevator, at the upper end of the main screw, and by pulleys on the under side of the walking beam a counterweight is hung beside the samson post. This weight balances the temper screw and renders its raising easy.

A device employing hydraulic feed and intended to replace the temper screw has been patented within the last few years. It is attached to the walking beam in the same position as the temper screw.

It is simple in construction and operation, as it consists essentially of a cylinder containing a piston to which the cable is attached. Water may be admitted either above or below the piston, and by regulating its flow from the lower to the upper part of the cylinder the piston and tools are allowed to descend slowly as the hole is deepened. When the piston reaches the bottom of the cylinder the tools and piston rod are again elevated to the top, a process similar to that of raising the temper screw in that it involves a cessation of drilling. With both devices, however, the adjustment is usually made only when the tools are withdrawn for sand bucketing the well.

The device has been patented too recently and used too little to enable one to judge of its merits. As it has a larger number of small and special parts than the temper screw, its use will not be approved by many drillers, for it may cause expensive delays when parts are broken. Accidents to the temper screw may usually be remedied by a local blacksmith. The new device is more easily manipulated than the temper screw, however, and this advantage may lead to its adoption.

CABLE.

Both hemp and steel-wire ropes are now used for drilling cables, the steel wire having come into more general use during the last ten or fifteen years.

The best quality of hemp rope is that made of manila hemp (not common hemp nor sisal) and is hawser laid, that is, it consists of three ropes of three strands each, twisted together into a single rope. In its manufacture a "nap" is formed, of the ends of hemp fibers, nearly all of which point toward one end of the rope. The rope socket should be fastened to the end toward which the fibers point, for although when the tools are attached to this end the fibers spread out and retard the downward stroke in a hole that is partly filled with water, they protect the rope better from being frayed by rubbing against the casing on the upstroke.

Steel-wire drilling cable is composed of several strands wound about a hemp center, each strand being formed of several wires. Rope consisting of six strands of seven wires each is a style commonly used.

The advisability of substituting steel-wire cable for hemp cable in drilling deep wells has been much discussed, some maintaining that hemp can never be replaced by steel, and others that steel will shortly be used altogether. The importance of the substitution of steel for hemp is better appreciated when it is known that a hemp cable ordinarily can not be used to drill more than one or two wells, but the hemp cable possesses certain important qualities which are not found in the steel cables and which must be considered in dealing with the

problem. The careful driller never allows his tools to fall as a dead weight on the rock which he is drilling, but so adjusts the rope that the tools will stretch it in reaching the bottom of the hole. The nature of this action may be illustrated by suspending a weight by a piece of rubber elastic a little above a table or other surface. It will be found that by giving a slight reciprocal motion to the rubber the weight may be made to strike the surface with considerable force. Manifestly, the force of the blow is diminished by this arrangement, but in drilling this loss of force is more than compensated by the springing blow that is struck; and if the rock is easily cut by the drill this rebound is essential, as otherwise the drill will be imbedded so firmly as to make it difficult to remove except by jarring.

In drilling a deep well the stretch of the rope is often underestimated, and it may happen that the tools are falling when the walking beam is rising, thus bringing a great strain on the cable and making the blows of the drill very ineffective. The operation of the tools is rendered still more difficult when the hole contains several hundred feet of water, which interferes with the free upward and downward motion of the cable.

Steel cable, with its smaller diameter and greater weight, has the advantage of passing comparatively freely through water which may stand in the drill hole, the water friction being much less than on a hemp cable, and the water also reduces the shock of the steel cable by acting as a deterrent to the rapid drop of the tools. On the other hand, steel cable has very little elasticity, and drilling by the stretch of the rope is hardly possible. Every blow that is struck by the drill is a dead blow, as there is no compensating rebound and the upward stroke causes severe strain, both on the derrick and on the cable itself where it is attached to the tools at its lower end and to the temper screw at its upper end. The difference in stretch of the two kinds of cable is shown by the fact that with a 5-foot temper screw 7 or 8 feet may be drilled with hemp cable, while at best a distance of only 5½ feet is possible with steel cable. Some drillers use 150 or 200 feet of hemp rope between the tools and the steel rope, and this gives some elasticity to the cable and rebound to the tools.

The use of the steel cable was considerably increased during the Spanish-American war by the fact that the price of hemp cable became so high that its use seriously increased the cost of a well.

In the last few years at least half of the oil wells put down in the California fields, where the wells are usually drilled "wet," have been drilled with steel cables. In other oil fields a very small proportion of the drilling is done with steel cables. For cleaning wells, however, it has largely supplanted hemp cable throughout the East, as in this work it is not necessary to use such a rapid stroke, and hence steel cable may be advantageously employed.

Experiments have been made by several supply companies looking toward the construction of some device that will give elasticity to a steel cable, but the thousands of dollars thus spent have had little practical result. Several experimenters, however, are continuing this investigation, working along the line of a spring fastened to the walking beam, the whole being adjusted in such a way that the spring, when given the proper tension, will take up the slack of the cable on the upward stroke and give it out again under the weight of the tools on the downward stroke. Experiments are also being made with a cushioned walking beam, looking toward the same result; and it is possible that a sufficient degree of efficiency may be reached in the construction of this device to permit the wider substitution of steel for hemp in future drilling operations.

The standard well-drilling outfit with steel-wire drilling cable has been used to some extent in the Baku oil region of Russia, where it was found that only a very limited amount of rotation could be imparted to a wire rope without damaging it, because of the untwisting and kinking of the strands. To overcome this disadvantage a special kind of wire rope was employed, consisting of left-hand and right-hand strands plaited together. It is said that this rope worked satisfactorily in the hands of a skillful attendant, but it had to be disconnected from the main drum at each change of operations.

DRILLING OPERATIONS.

SPUDDING.

The term "spudding" is often misunderstood. By some people it has been thought to mean the preliminary part of drilling, without reference to the way in which the drilling is conducted; by others it has been interpreted to mean drilling in rock of unusual hardness. Properly, however, the term is applied to drilling without the aid of the walking beam—the method nearly always used in sinking the first 75 or 100 feet of a well, as the string of tools is too long to be operated from the walking beam in beginning work. It is possible to attach the tools to the drilling cable before the hole has been drilled to this depth, but owing to the short length of cable between the tools and the walking beam there is very little "spring" in the rope, and the hole must be spudded to a sufficient depth to allow a considerable length of cable to come between; otherwise the blow of the drill will be "dead" and the rope will be likely to break.

For spudding a short cable is run through the crown pulley at the top of the derrick, one end being attached to the bull-wheel shaft and the other to the rope socket, to which are usually screwed only the auger stem and spudding drill. The drill may be given an up-and-down motion in two ways: In the first method the rope is carried

around the bull-wheel shaft in two or three turns, its end being left free. A man standing in front of the bull wheels grasps this free end of the rope and gives a slight pull, causing the coils to tighten and grip the revolving shaft, and by this means raising the tools; when the rope is slackened the tools fall. By alternately tightening and slacking the rope the operator may raise and drop the drill. The second method has come into use comparatively recently and is much more effective than the other. In this method, which is self-adjusting, the drill rope is wound firmly about the bull-wheel shaft and passed through the crown pulley, and from its end the tools are suspended in the drill hole. A rope called the jerk line is attached to the wrist pin of the band-wheel crank, brought inside the derrick,

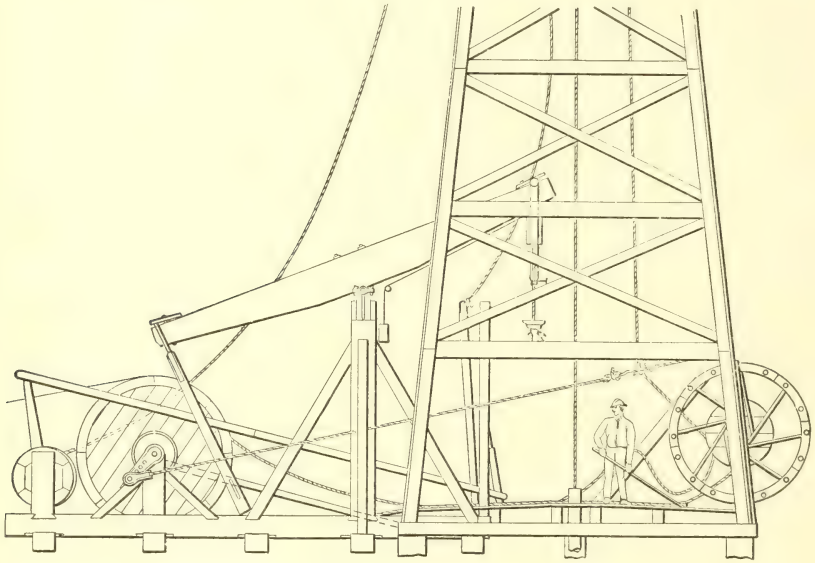


FIGURE 8.—Standard rig arranged for spudding.

and attached to the part of the drilling cable which extends from the crown pulley to the bull-wheel shaft by a curved metal slide called a spudding shoe. (See fig. 8.) By carefully adjusting the length of this rope each revolution of the band wheel results in a pull on the line and its subsequent release, and a corresponding rise and fall of the tools. As the hole is deepened the cable is let out by giving the bull-wheel shaft a partial revolution, and the spudding shoe is slipped farther and farther down, for this downward sliding of the spudding shoe increases the length of the pull on the drilling cable and hence the distance through which the drill drops. The sliding motion is imparted by the driller's assistant, between the jerks of the line, by means of a crooked stick long enough to reach the spudding shoe from the floor of the derrick.

Spudding is much harder on the derrick than is ordinary drilling, as the strain is brought on the top of the derrick where there is the greatest leverage. In drilling with the walking beam the weight comes on the samson post, which is not directly connected with the derrick, and the strain comes on the derrick only when raising or lowering tools or casing and when using the sand bucket or the bailer.

DRILLING WITH THE WALKING BEAM.

After the hole has been sunk to the depth required for the string of tools a heavier drilling bit is attached, the drill rope is suspended from the walking beam by the temper screw, and regular drilling by means of the walking beam is begun. To allow freedom of motion to the walking beam, 20 or 30 feet of the drill rope are unwound from the bull-wheel shaft and loosely coiled on the floor. The pitman of the walking beam is then fastened to the wrist of the band-wheel crank. The crank is provided with a number of holes, so that the length of stroke can be adjusted to the depth of the well, a short stroke being used near the surface, as the strain would otherwise be too great for the rope to bear. The engine is then started and the walking beam begins rocking up and down, raising and dropping the tools at the rate of about 25 strokes a minute.

Until within the last few years it was the custom to revolve the drill by inserting a stick in the rings below the temper screw and slowly turning the rope first in one direction and then in the other. This was thought to insure a round hole by causing the drill to strike each time in a different place. One day a tired workman, who wondered if this operation was necessary, neglected this precaution and found that the drill still made a round hole, a fact that had often been inferred by drillers who had seen the tools revolve and bring the drill in a new position for each stroke. The drill is jerked free from the rock unevenly, and the torsion of the drilling cable under the lifting strain has the effect of rotating the tools in one direction on the upstroke and in the other on the downstroke. This action, however, takes place to a notable degree only when there is a sufficient length of rope between the tools and the walking beam; until a considerable depth is reached it is often necessary to turn the cable by hand, otherwise the drill may strike successive blows in the same place, but it is now rightly considered that after the hole is 200 or 300 feet deep it is needless to turn the rope while drilling.

The skilled workman takes hold of the rope or swivel often, for by the feel of the rope he ascertains whether the string of tools is intact and the drill is cutting the rock. When the drilling bit strikes the bottom of the well, the cable is drawn taut and conveys the vibration to the driller's hand; by this means he soon learns when to

adjust the temper screw. In the same way the operator learns whether or not the jars open and shut at each blow of the drill.

The proper tension of the cable can be determined only by practice. An old cable has more spring to it than a new one; and the weight of the drilling tools, the depth of the hole, and the speed at which the machine is running must also be taken into consideration. Ordinarily the engine should be speeded up until the cable tightens slightly in advance of the stroke of the drill, not so as to retard its fall, but so that when the drill touches bottom it will be instantly lifted, with no time either to settle or stick. This careful adjustment of the stroke is absolutely necessary for rapid and skillful work. If the drill touches bottom when at rest, there is too much rope out and it should be taken up with the temper screw, for the downward stroke of the drill will stretch the rope sufficiently to let the bit strike the bottom of the hole.

The motion of the drill will be greater than that described by the walking beam, unless too much cable is let out, in which event the stroke of the drill will be less than the stroke of the walking beam, the strain on the cable will be greatly increased, and little or no progress can be made. One of the hardest things for a beginner to learn is that he can not make the drill cut faster by letting out more cable. With a hemp cable, at a depth of about 50 feet, when the drilling tools are at the lowest point in the stroke, the point of the bit should hang 2 or 3 inches above the bottom of the hole. At 100 feet it should be 4 or 5 inches; at 200 feet it should be 6 to 12 inches; and at greater distances with greater depths. An unskilled driller will sometimes allow the full weight of the tools to fall on the drill rope, the drill actually being stopped in its descent a short distance above the rock in which it is supposed to be cutting. The likelihood of such an occurrence increases with the depth of the hole, for the increasing weight of the drill rope added to the weight of tools, often several tons in all, makes it difficult to detect by the "feel of the rope" whether or not the total weight is decreased at the end of the stroke by the weight of the tools below the jars.

As the drill cuts deeper it is necessary to let out the drill rope gradually, so that the drill will strike bottom at each stroke. This is done by loosening the yoke clamp a little, and running out the temper screw a turn or two. At the end of from half an hour to several hours the temper screw has been run out its length of several feet and the drill has advanced an equal or greater distance. The tools are then withdrawn, the waste that has accumulated since the last bailing is removed with the sand bucket, and if necessary a sharpened bit is substituted.

The withdrawal of the tools is accomplished by first taking up the slack cable on the bull-wheel shaft, thus transferring the weight of

the tools to it through the crown pulley. The rope clamp is then loosened, the temper screw is disconnected, and the pitman is thrown off from the band-wheel crank pin, as in figure 8. By rotating the bull-wheel shaft with the engine connection, the tools may then be raised or lowered at will. This part of the work demands skill, for if the bull-wheel brake should not be applied as the tools reach the surface, the crown block and pulley would be torn loose and the tools would fall on the workmen beneath. After the tools are clear of the hole, they are swung to one side and caught in the loop of a quarter-inch rope fastened to a leg of the derrick.

The operator is now ready to bucket the drillings from the well. The sand bucket, or bailer, consists of a section of tubing 15 to 60 feet long and somewhat smaller than the well. It has an iron valve at the bottom, either of the flat pattern, or the ball and tongue pattern. (See fig. 6 [8-9].) In some materials in which the drillings are thick and heavy and do not readily enter the bailer, a sand pump (fig. 6[10]) is used. In addition to the bottom valve this has a plunger which is worked like that of a water pump, and thus sucks the drillings into the tubing. The bucket or pump is suspended from a wire cable that is wound on the sand-line reel and carried through the sand-line pulley. The reel is operated from the derrick by a lever, which brings its friction pulley into contact with the band wheel. The sand-bucket line is thus wound up and the sand bucket is swung over the hole. The friction bearing on the band wheel is then released and the bucket is lowered into the well at any desired speed. As the drillings form a thin mud, owing to the addition of water from time to time by the driller, they rise into the sand bucket, are retained by the valve in its bottom, and are then removed. The bucket is emptied by lowering it upon an upright stake or pin beside the well, thus opening the valve.

The liquid condition of the drillings often makes it possible to drill 5 or 6 feet without bucketing; otherwise the drill would become ineffective at the end of a very short time, by striking into its own cuttings, and the necessity for frequent bailings would greatly increase the work and cost of drilling. Water is usually added to the drillings by the bucketful at the well head. Sometimes it comes into the well from water-bearing strata that have been penetrated by the drill in a quantity sufficient to soften up the drillings, and yet not great enough to interfere with the work. It is then unnecessary to pour in water from the surface.

In many localities water is added to the drillings by means of a barrel set at one side of the derrick, from the lower end of which a pipe extends within 2 or 3 feet of the drill hole; to this pipe is fastened, by a loose joint, another piece of pipe as long, at least, as the height of the barrel and long enough also to reach from the end

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of the horizontal pipe to the mouth of the drill hole. When the short length is dropped to a horizontal position water flows from the barrel down into the hole; by raising the short pipe to a vertical position the flow is shut off.

DRESSING THE BIT.

As the bit gradually becomes worn on the edges, its diameter is constantly reduced—that is, it loses its gauge. When the tools are withdrawn, if the bit has become noticeably worn, the screw joint connecting the bit and auger stem is "broken" by means of the wrenches and floor circle, the bit is unscrewed and removed by hand, and a freshly dressed bit is then substituted. During the first part of this operation the tools are steadied by keeping them partly in the drill hole. At this time the whole string of tools is usually examined, and each joint is "set up" in turn, as the constant and tremendous jarring to which the tools are subjected tends to loosen the different parts. Before drilling is resumed the temper screw is also screwed up or "elevated" so that it can be fed down as the drill hole deepens. The tools are then let down again and drilling is resumed.

The worn bit is heated in the forge, the circular tool gauge is slipped over while it is hot, and the edges of the drill are hammered out to fit the gauge, which has a diameter one-eighth inch greater than the required diameter of the bit to allow for contraction due to cooling. In heating the bit it should be turned occasionally to get an even heat, and brought to a cherry red for a distance 3 or 4 inches back from the end, so that in hammering it the outer part will not tend to spall off. It is usually spread with a sledge, working from the center to the edges, to a diameter a little larger than the gauge, and then hammered down to proper size. The edge should not be made very sharp or it will tend to drill a three-cornered hole. In tempering the end is heated until it shows bright cherry red in the shade, then placed upright in 1½ or 2 inches of water so as to cool only the part to be tempered. After a minute or two, when the edge is cool, the bit is removed until the heat flows back into the end and causes it to pass through straw, orange, and purple to a blue color. It is then re-immersed and allowed to cool. The treatment gives the proper temper for drilling moderately hard rock. If the bit is cooled at one of the colors that appear earlier, it will be too hard and brittle to work well, and if allowed to wait longer before tempering it will be too soft. The upper (threaded) end of the drill should be thoroughly cooled before it is screwed to the stem, otherwise subsequent shrinkage may cause the joint to loosen.

As the bit becomes worn by continued drilling, the size of the hole is correspondingly decreased. In hard sandstone one-quarter to three-

eighths of an inch may be worn from the width of the bit in drilling 3 or 4 feet, so that when a newly dressed bit is introduced it may find the last few feet too small, and may work hard or even stick for the first few strokes. A well-worn bit will cut a hole no larger than its shank, but a newly dressed bit provides clearance, like the teeth of a newly set saw. To prevent sticking the bit is run up and down a few times and turned constantly. It is thus prevented from forming a groove which it would tend to follow so as to direct the repeated strokes of the drill in the same place. When the rock is very hard and the bit is more rapidly worn jars are necessary to prevent accident to the drill rope by the sticking of the drill.

WET AND DRY DRILLING.

A "wet" hole is one in which water in excess of that required for the operations is present while drilling; a "dry" hole is one in which excess water is cased off during the sinking of the well. In oil fields these terms are applied in a different sense, a wet hole being a well which yields oil and a dry hole one which does not.

In a dry hole the drilling can be done faster, as the tools are not buoyed up by water; the rope lasts longer because it is not always saturated; small showings of gas and oil are more readily detected and their depths are more accurately determined; and if the tools are lost in the hole, they can be more easily recovered, as fishing tools are used to better advantage in a dry than in a wet hole. At Bartlesville, Okla., three water-bearing sands are encountered in drilling for oil. Dry drilling in that field is regarded as so much more satisfactory than wet drilling that three strings of casing are inserted to keep the water out. Two of these are withdrawn when the well is completed, the last one that is inserted being kept in service to retain the oil and prevent the well from caving.

Wet drilling is usually cheaper (there being no outlay for additional casing), no time is lost in putting in casing and replacing the tools by a smaller set; and when the well is down, the charge of nitroglycerine used in shooting the well has much greater effect, as it is tamped by the heavy column of water. The greatest disadvantage of wet drilling is that the sides of the hole are kept so wet that some of the shales are reduced to a semifluid mud, which frequently caves. Another disadvantage is that when tools are lost there is danger of sand and mud settling around them, even if the sides of the well do not cave.

CASING THE WELL.

CONDUCTOR BOX.

In many places the surface material consists of loose sandy clay, sand, and gravel, varying in thickness (in the Pennsylvania oil regions) from a few feet on the hills to several hundred feet in the

valleys. To restrain this material, which would otherwise impede the work of drilling, a conductor box, made of plank, circular, square, or octagonal in shape, and 8 inches to 20 inches across, is sunk to the bed rock. If the rock lies only a few feet below the surface the necessary excavating is done by hand; if the soil is deep, a large drilling bit is used to spud down a hole, into which the conductor box or a section of large iron pipe may be sunk as fast as drilling proceeds.

CASING AND DRIVE PIPE.

After passing through the surface material the drill enters the "live" rock. As a rule this rock is made up of alternating layers of hard and soft, of very porous and slightly porous, of water-bearing and nonwater-bearing rock. Unless the water in the rock is under notable head and is considerable in amount, it is welcomed by the driller, as it saves the trouble and expense of pouring into the hole sufficient water to keep the drillings liquid. If, however, the water coming into the hole is too great for rapid drilling, it is necessary for the driller to insert a string of casing extending from the surface into the first hard, nonwater-bearing rock that is encountered after passing through the water-bearing layer. This casing is set very firmly into the hard layer and shuts out the water. In order to continue drilling, it is necessary to use a smaller bit which will pass, with clearance, inside the casing. If other heavy flows of water are encountered at greater depths, each flow must be cased off by a string of casing extending from the surface to the bottom of the water-bearing layer. As each string must slip inside the preceding one, a smaller drill must consequently be used after each casing operation.

The first well lining used in this country was in the celebrated well drilled by Colonel Drake on Oil Creek, Pennsylvania. Some of the early drilled wells of small diameter were lined with pipe made of riveted or soldered sheets of copper. Before long this was superseded by drive pipe with soldered brass screw joints, such as is still used in the salt wells of Tarentum, Pa.

Several varieties of casing are now used. Sheet-iron riveted pipe is extensively employed in the Russian oil fields, but it is little used in oil wells in the United States. It is rather short lived, and the corners of the bit are apt to catch on it in drilling and cause breaks. Another kind of pipe used, known as oil-well casing, ranges in usual sizes from 4 to 12 inches, inside diameter, and is made in several weights. A third kind, called steam pipe, is also made in sizes up to 12 inches and in three grades—standard, extra strong, and double extra strong. Still another kind of lining is the regular drive pipe, which is made very heavy in order that it may be driven to great depths. The ends of the pipe are cut off smoothly and meet squarely in the middle of the sleeve coupling (fig. 9[1]). In this way the

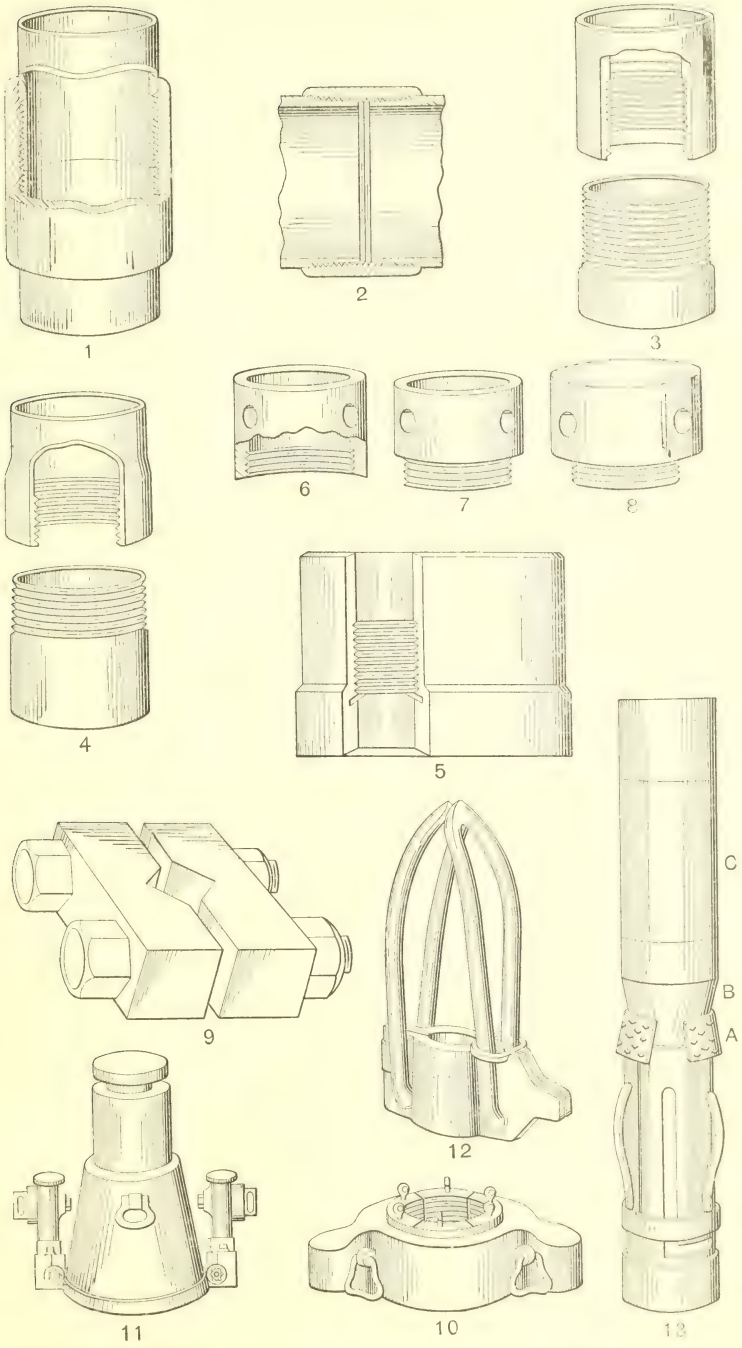


FIGURE 9.—Couplings and casing attachments. 1, Sleeve coupling; 2, tapered sleeve coupling; 3, 4, sleeve and inserted joint couplings; 5, shoe; 6, 7, 8, drive heads; 9, drive clamps; 10, pipe ring; 11, hydraulic jack; 12, elevator; 13, gas packer.

whole strain in driving comes not on the threads, but on the pipe; otherwise the joints would be disabled before reaching any considerable depth.

If a cheap well is desired, heavy wrought-iron pipe is driven to rock, and the well is finished by drilling to the required depth. A casing made of sheet iron, one-sixteenth inch thick and one-half inch smaller than the drilled hole, is then used. If it is necessary to shut off sand the bottom of this pipe may be flanged outward a little. After the sheet-iron pipe has been placed in the well the heavy pipe may be pulled out and used again. If the depth to rock is not more than 50 or 75 feet and the material is all clay or earth which will not cave, the heavy pipe may not be used at all, the sheet-iron pipe serving in its stead, though its use in this way is attended by considerable risk.

Casing is usually a lighter and cheaper pipe than drive pipe, as it has little outside pressure to withstand. A tapered sleeve coupling (fig. 9 [2]) is often used with it. In this form of coupling the last thread in the tube is the weakest and most likely to break in case of accident, and the pipe is easier removed than if the whole thread remained in the tube. Flush joint and inserted joint couplings (fig. 9 [3-4]) are also used with casing that requires little driving. After a few wells have been sunk in a district the approximate amount of casing that will be required for a well can usually be estimated, since the depth to troublesome water-bearing formations is then roughly known.

In gas wells, where dryness is essential, all the strings of casing are usually left in the well to prevent water near the surface from sinking to the lower end of the last casing, where it would be under great head and might force its way through a weak spot at the point of juncture of the casing with the rock. As a cubic foot of water weighs about 62½ pounds, the pressure, in pounds per square inch, of the column of water in the drill hole is equal to the height of the column in feet, multiplied by 0.434. Therefore at the bottom of a well 1,500 feet deep water that enters and fills it up to the 500-foot level exerts a pressure of 434 pounds per square inch. This is the crushing stress on the pipe provided there is no internal column of liquid to counterbalance the external column, as, of course, there is not in a producing gas well.

In deep drilling, where caving material may be encountered, it is customary to sink casing, or drive pipe, as fast as drilling proceeds. For this purpose pipe heavier than the usual casing is employed, and stronger joints are made generally by heavy sleeve couplings (fig. 9 [1]). On the bottom of the lower joint there is screwed or shrunk a shoe of tempered steel (fig. 9 [5]), which will stand heavy driving without injury, and which gives clearance for the pipe and couplings.

The ordinary pipe would be greatly damaged in driving long distances if it were not protected by this shoe. To prevent the top of the pipe from being battered, a drive head (fig. 9[6, 7]) is screwed or placed on it. In some places the material is so loose that the tubing will follow the drill for some distance without requiring to be driven; but when driving becomes necessary drive clamps (fig. 9[9]) are bolted to the pin square of the upper end of the auger stem. The machinery is then coupled as for spudding, and 50 or 60 blows a minute are delivered by this driving clamp to the drive cap on the top of the pipe. The pipe may also be driven by a heavy wooden maul attached to the drill rope. In this case a solid drive head (fig. 9[8]) is used, and proper direction and effectiveness are insured to the blows by means of temporary guides set within the derrick.

Sometimes in drilling through a compact formation, such as clay, the pipe becomes lodged, owing to the projection of the couplings. When this happens a cap is screwed to the drive pipe, and water is forced down it so as to come up outside of the pipe and loosen the material about the coupling.

When the pipe has been driven as far as practicable drilling is resumed. The driller endeavors to keep the hole sunk a few feet ahead of the casing, for in this way the casing is let down straight, whereas if the pipe is driven ahead of the drill, it may be deflected from its course by changes in the hardness of the material or by encountering a bowlder or a layer of coarse gravel.

This method, however, can only be used where the material will stand up for some distance without the support of the pipe. Quicksand will flow around the bit and even rise in the pipe, and in this material the pipe must be driven down to the bottom of the hole and kept ahead of the drill. If the bed of quicksand is not thick, the difficulty of drilling through it will be slight, but where beds 50 or 60 feet in thickness are encountered, some of the greatest difficulties known to well engineers have to be met and overcome.

When long and difficult strings of casing or drive pipe are to be withdrawn or "pulled" from a well, as on completing or abandoning it, a pipe ring (fig. 9[10]) is placed over the upper end of the pipe; this ring grips the casing firmly by means of its corrugated iron wedges and is then subjected to upward pressure by specially designed hydraulic lifting jacks. (Fig. 9[11].) When short or easily pulled lengths are to be removed, wrought-iron elevators (fig. 9[12]) are clamped to the upper end of the last length of pipe, are caught by a hook suspended from the derrick, and are tugged upward by means of pulley sheaves.

Several machines for pulling casing are on the market. For pulling casing from abandoned wells they have the great advantage of portability, and they are cheaper and more efficient than a derrick erected over the well.

PORTABLE DRILLING RIG.

VARIATIONS IN CONSTRUCTION.

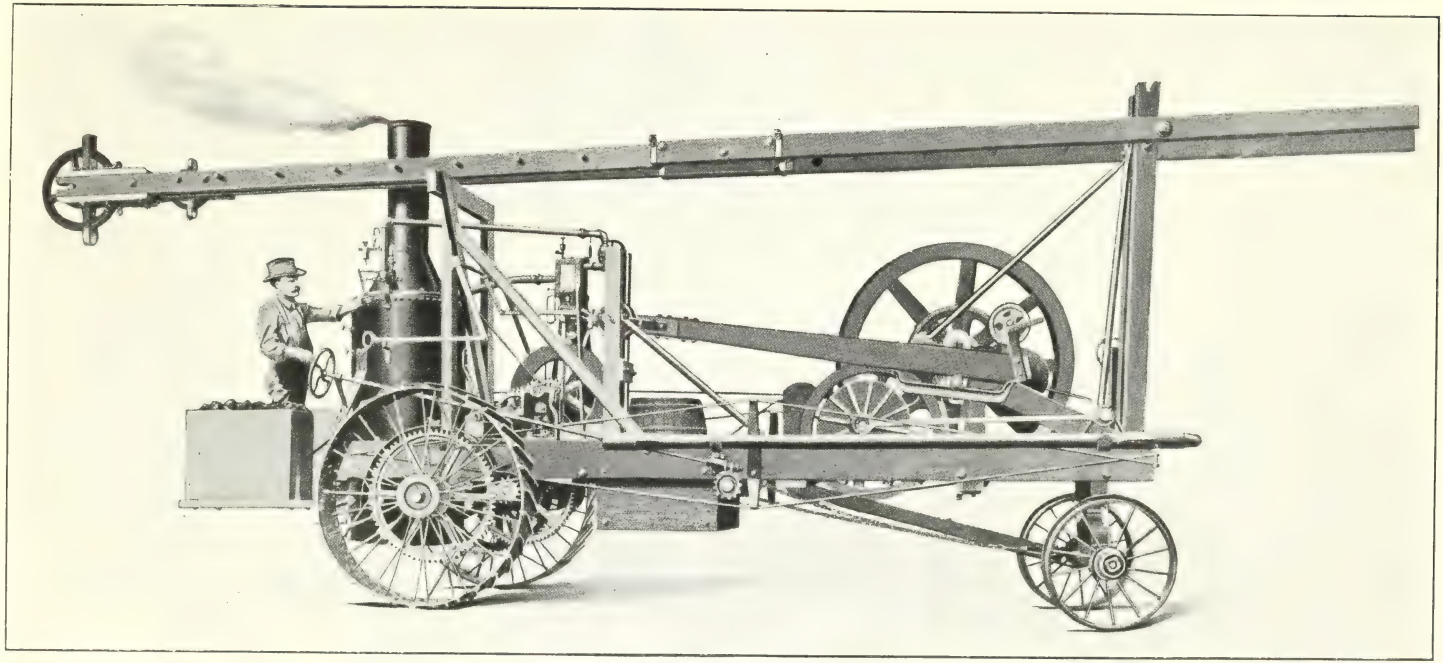
Several modified forms of the standard outfit, called portable rigs, are made. These rigs are built in compact form, on heavy frames, and are usually mounted on wheels. Horses are commonly employed in moving these rigs, but in favorable localities a traction engine supplies power for the machine when in operation and hauls it when it is to be moved. A steam or gasoline engine is used, and the engine may or may not be mounted on the frame with the other machinery.

In mode of operation and in the kind of tools used these portable rigs are like the standard outfit, but most of them are lighter and they can not be used to drill to as great depths. Certain parts of the machinery, such as the hoisting gear and sand reel, are usually placed within the frame, and are operated through either cog or friction-power transmission.

The difficulty of weight in transportation is one which the manufacturers have been working for a long time to overcome. Every part of such rigs has been carefully tested and the experience of operators taken into account, so that machines made at the present time represent the maximum strength with the minimum amount of material, and any decrease in the weight of any part would mean a decrease in effectiveness and durability. The total weight of a portable rig is usually about 15,000 pounds, though lighter outfits may weigh only 5,000 pounds, and some of the heavier ones weigh 20,000 pounds or more.

In most portable machines support for the hoisting sheave is provided, not by a derrick, but by a mast, which is erected over the front of the rig, and brings the sheave over the spot where the well is to be drilled. In hauling the machine from place to place the mast is tilted back over the machinery, as shown in Plate II.

To make the portable rigs more compact the walking beam is made 2 to 6 feet shorter than the walking beam of the ordinary standard rig. The shortened stroke which results becomes a disadvantage only when the hole reaches considerable depth. In the first few hundred feet the stretch of the rope is so slight that the short walking beam is nearly as efficient as is the usual walking beam of the standard rig; at greater depths the total stretch of the rope is so increased that unless the stroke of the walking beam is correspondingly lengthened the machine will drill on the tools; that is, when the walking beam is coming up the tools will be going down. If the walking beam is properly adjusted, however, drilling may be conducted to a depth of 1,000 or 1,500 feet. Beyond 1,500 feet the stroke of most portable machines becomes so short as to make them less efficient than the standard outfit.



PORTABLE DRILLING MACHINE, USING STEAM-POWER TRACTION.

Showing derrick folded, spudding bar, etc.

A technical description of the details of each of the many styles of portable well-drilling machines can not be given in this report, and it would be obviously improper here to designate by name those supposed to be the best or those having manifest disadvantages. Each rig includes some device which makes it in certain respects superior to others, but no portable well-drilling machine is perfect. Unfortunately the invention of a new device usually results in building a new machine, and the embodiment of all good devices in one nearly perfect machine is impossible on account of patents.

The leading portable drilling machines are so fully described in the manufacturers' catalogues that a driller can readily note the important points and advantages of each style. Some rigs have special devices for rapid spudding, as spudding is in many wells carried to a depth of 100 feet, or even more, and forms so large a part of the sinking of wells less than 1,000 feet deep. One way of obtaining a spudding motion is shown in figure 8. Some rigs have devices to shorten the time for changing from drilling to bailing, such as variations in the form of the pitman, so that it need not be disconnected from the crank pin in changing from one operation to the other. Others have special devices for deep drilling. Several portable rigs are adapted to using self-cleaning or hollow-rod tools, and one or two are fitted to operate hydraulic rotary and core-drilling tools.

ADVANTAGES AND DISADVANTAGES.

Most portable rigs are not intended for deep, heavy work and do not come into competition with the standard outfit, though of late years heavy, semiportable rigs with a capacity of 2,000 feet or more have been built for oil drilling. Both portable rigs and the lighter styles of the standard outfit are used in drilling wells between 500 and 1,500 feet in depth.

Portable rigs are often used in cleaning out oil wells, which are also cleaned by erecting derricks over them and stringing the tools as in beginning a well; but as the work involved in cleaning is not very great a lighter and cheaper outfit than the standard can be used to advantage.

Portable rigs are also used in prospecting for gold in Siberia, Australia, Argentina, and South Africa, and in drilling blast holes for large excavations such as the Panama Canal.

The chief advantage of a portable rig is that it can be easily and cheaply moved after the well is completed, whereas a standard outfit must be torn down and rebuilt for use in a new location.

In some localities, as in southern Illinois, where the country is flat and the difficulties of transportation during the rainy season are great on account of muddy roads, drillers with standard outfits are usually

able to tear down and rebuild the derrick in a shorter time than would be required to haul a portable rig to a new location and set it up. Drillers near Casey, Ill., claim that they can set up a standard outfit twice and drill two wells with it in the same time that one well can be drilled with a portable rig. The standard derrick used near Casey is 60 feet high and is built of light timber in skeleton form, except in stormy weather. This outfit will drill a hole 500 feet deep in about five days; a portable rig would consume ten to fifteen days.

When made in this light form the standard rig is taken down in sections, each of which is placed on a pair of trucks and hauled from place to place more easily than a portable rig, which must be moved as a whole.

Once in position the standard rig is preferable to the portable on account of its greater rigidity, the larger space it affords for handling tools, oiling bearings, and repairing broken parts, and the better protection it gives during stormy weather. The compactness of some portable rigs makes it difficult to oil or adjust the machinery while in operation without danger, or at least without great discomfort, to the workmen. The extra work of lifting large wrenches and drill bits to the drilling platform when adjustments are necessary is also very considerable. Breakdowns with a portable rig are annoying and expensive, as the driller must often send to the factory for the broken part; whereas most breaks in a standard outfit can be repaired by a local blacksmith or carpenter, or by the workmen themselves.

With portable rigs the bits are dressed in the open, and there is no shelter for men or tools from sun or rain. Shelter can of course be provided for both rigs, but more easily for the standard, since the derrick posts form a frame that needs only to be boarded in. Owners of portable rigs expect workmen to do without a shelter, but the shed is a usual part of the standard outfit. If a shelter always had to be built for a portable rig the extra labor required would leave little advantage in favor of this machine. The flywheel and gearing, however, are often protected in rainy weather by a lean-to.

Much of the difficulty that has attended the use of portable machines may be attributed to the fact that the men engaged to operate them have been accustomed to standard outfits and are prejudiced in their favor. Drillers have been severely criticised by manufacturers and well owners because of this prejudice, asserting that every improvement devised was condemned by the drillers because it was novel and at first somewhat difficult to manipulate. In a measure this is true, but it should be remembered that these men are trained in the oil fields of Pennsylvania, Ohio, Indiana, and West Virginia, where the standard outfit is largely or exclusively used, and, having slight knowledge of mechanics aside from that gained in actually operating standard outfits, they look with disfavor on portable rigs.

A man who begins his drilling experience with a portable rig is always enthusiastic over the machine and its possibilities. This is especially true of drillers of water wells ranging in depth from 400 to 500 feet.

That portable rigs are adapted to a wide range of conditions is shown by their general use. In drilling for water, oil, and gas they have been successfully employed in every part of the United States, and in drilling for water they are used in nearly every country in the world.

PERCUSSION CORE DRILL.

Within the last few years a percussion core drill, designed to obtain a core when prospecting coal and other relatively soft deposits (see p. 30), has been put on the market by a manufacturer of portable drilling machines. This drill is substituted for the ordinary drill after the hole has been sunk nearly to the material of which a sample is desired.

The drill consists essentially of a hollow tube or bit stem armed with a toothed cutting bit, a core barrel, and a weighting bar. The teeth of the bit are "set" alternately in and out, like those of a hand saw, so as to give clearance to the drill on the outside and to the core within. The core barrel is a tube, about 4 feet long, that slides within the bit stem. It has a split ring near the bottom, which grips the core when the tools are withdrawn. As sinking progresses a weighting bar forces the core barrel down over the core and protects it from abrasion. (See fig. 10.)

The chief advantages claimed for the attachment are its adaptability to the ordinary portable drilling outfit; the large core yielded, as the device is made chiefly for 5⅝ or 6 inch tools; the ease and rapidity of withdrawing tools, as they are on a cable, not on jointed rods; and special adaptation to taking samples of very soft material. It is not intended for work in very hard rock nor in localities difficult of access.

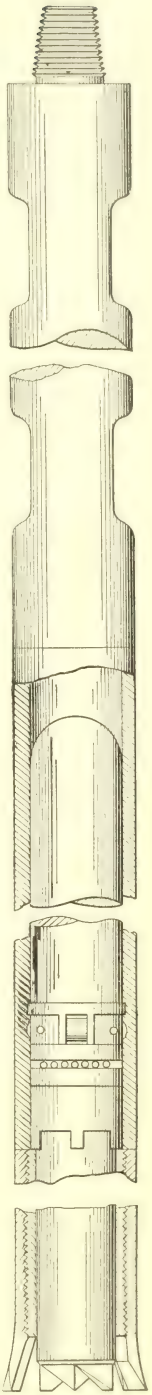


FIG. 10.—Percussion core drill.

POLE-TOOL METHOD.

GENERAL FEATURES.

The pole-tool or wood-rod method of well drilling is old and, in some respects, rather primitive, representing an early stage in the development of churn

drilling. It differs from the standard method chiefly in using wooden rods instead of a cable for operating the tools.

Previous to the introduction of hemp cable the pole-tool outfit was much used in England and France, where it is still employed to some extent; but in the United States it has been largely superseded by cable rigs. It is, however, still used in this country for sinking water wells in certain regions, especially in the area between Illinois and Montana and north of Kansas and Colorado, where the great depth of the wells and the large amount of water encountered make the retention of wood rods advantageous in drilling wet holes. If a portion of the hole is drilled dry, a cable is attached and drilling is conducted as with the standard outfit; but the friction of 1,200 or 1,500 feet of hemp rope in as many feet of water so greatly reduces the force of the blow on the rock that a pole-tool outfit may be more advantageous.

When a cable rig is used in a hole containing considerable water the friction may be reduced by tarring or oiling the rope so that the fibers can not spread. This treatment, however, affords only a temporary remedy and but slightly decreases the friction of the rope. By using wooden rods the friction is greatly reduced, and the drill can be operated much more efficiently.

In the oil and gas fields of Pennsylvania and Ohio it is desirable and often necessary to keep water out of the hole, either because the operator can drill faster in a dry hole or because he must exclude water from the oil sands; but in North and South Dakota, Wisconsin, and Illinois, where the pole-tool outfit is in use, the driller is drilling for water and may desire to retain all flows he may pass to supply the completed well. A cable rig could be satisfactorily used only by casing out the water, drilling the hole to the depth necessary to guarantee a sufficient supply, and then drawing the casing or perforating it to allow the water access to the well. Experience has shown that under ordinary conditions the expense of the casing and of the increased labor required in drawing or perforating it, when drilling water wells with the standard outfit, exceeds the cost of drilling with the pole-tool outfit, in spite of the extra labor involved in the actual drilling with the latter.

The necessity of maintaining the initial diameter of the rods prevents drilling a hole as small as that which can be drilled by means of a cable. If the hole is full of water and its size is decreased to 3 or 4 inches, drilling is greatly impeded by the long column of water that rises and falls with each stroke of the drill. The diameter of the hole, therefore, can not be reduced below the size which gives ample clearance between the rods and the well wall. In the pole-tool method the drill falls on the rock at the bottom of the hole as a dead

weight, and a springing blow can not be struck as when drilling with a cable. This reduces the speed of drilling considerably.

OUTFIT.

A derrick about 60 feet high and 16 feet square at the base is used with the pole-tool outfit. It resembles the standard derrick in most respects and requires about ten days to set up and two to four days to take down.

The string of tools of the pole-tool outfit, like that used with cable outfits, consists of socket, jars, auger stem, and drilling bit. The rods, which are substituted for the rope, are 2 to 3 inches in diameter. Each length of rod consists of two 18-foot pieces, spliced together and reinforced at the joint by irons. (See fig. 11, *C*.)

Jars are used to prevent the weight of the rods from coming on the drill, and also to prevent the crushing of the rods under their own weight. Before the invention of jars this battering and crushing was a constant source of trouble in well drilling with rods, and was the chief cause of the numberless fishing operations of early days. The jars, therefore, can not be discarded from pole-tool outfits as they sometimes are from cable outfits.

As with the standard outfit a walking beam is used, and the length of stroke is controlled by changing the length of the crank; but a ratchet on the walking beam, operated by a crank and lever within easy reach of the driller is used instead of a temper screw for feeding the drill. (See fig. 11, *A*.) A chain runs from the drum of the ratchet over the end of the walking beam and is connected with the rods by means of a swivel.

DRILLING OPERATIONS.

While drilling, the tools are constantly rotated so as to keep the joints on the rods tight and the drill hole round, for there is not sufficient natural torsion in the rods, as there is in a cable, to keep the drill from striking twice in the same place.

In drawing the rods, the whole string is raised by means of a hemp cable with swivel attachment, operated through a pulley at the top of the derrick. When the first joint appears above the top of the well head an assistant sets the square end of the joint iron into a wrench laid in the socket of the wrench block. (See fig. 11, *B*.) The wrench tightly fits this socket in the block and is prevented from turning when the rods are turned by a small iron post, the arrangement serving the function of the wrench and floor circle used in the standard outfit. With another wrench a second workman unscrews the swivel by which the raising cable has been attached to the upper rod, and this rod is unscrewed from the one below and set at one

side of the derrick. The wrench that is fitted on the square end of the second rod previous to detaching the first length prevents the whole string of rods and tools from dropping into the bottom of the well when the first length is removed. The swivel is then lowered and screwed to the upper end of the second length of the rods. These are drawn up so that the square joint iron of the third length fits

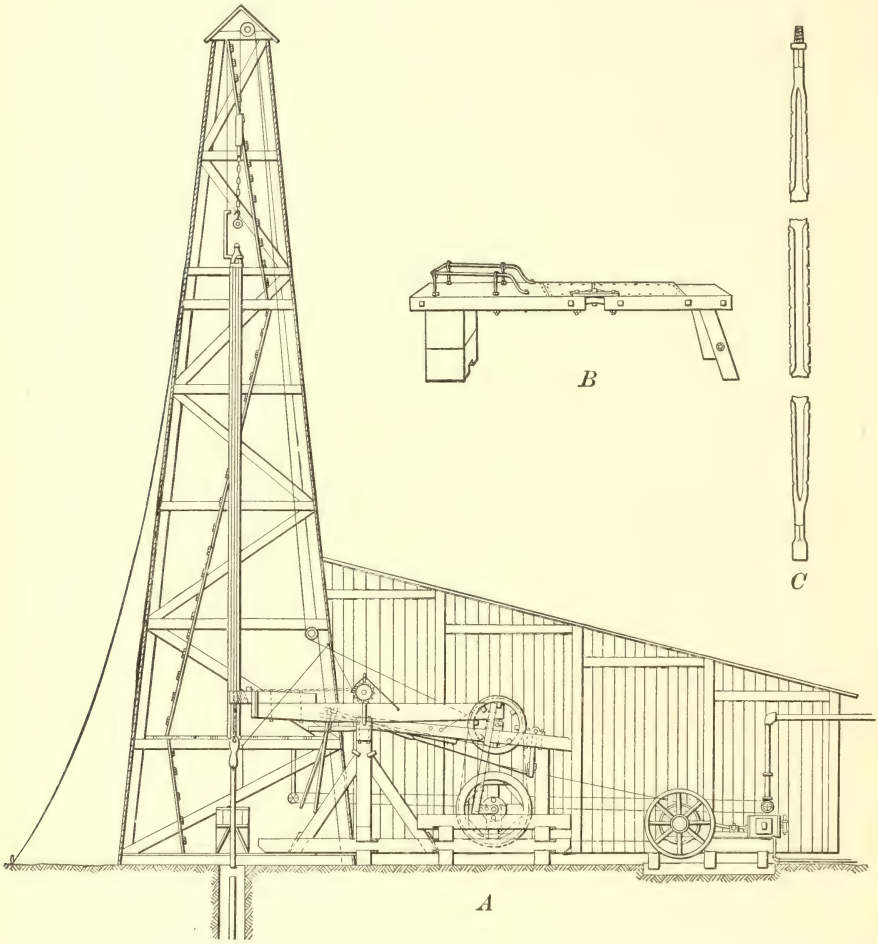


FIGURE 11.—Canadian pole-tool outfit: *A*, Side elevation; *B*, wrench block; *C*, drill rod.

into the wrench, and the whole string of rods and tools is held by it while the second joint is being unscrewed. In the same manner the entire string of rods is raised and taken apart. This operation makes it necessary for one workman to be in the derrick about 36 feet above the surface of the ground, but in this position he is able to help the man at the well head in steadying the rods and setting them to one side, and in guiding the descent of the lifting swivel.

In raising and lowering the tools the men work rapidly, though two of the three men needed in operating the outfit are busy only during the time that the drill or bailer is being raised or lowered. There appears to be great waste of time in this method of drilling, especially in bailing the cuttings, for which purpose a steel cable might well be used when the drillings are thin, as the bailer can be made of a size and weight to cause it to sink to the bottom of the well without difficulty. At least an hour is spent in raising the drill out of the hole, lowering the bailer, redrawing it, and resuming operations with the drill. Each one of these four operations involves the unscrewing and screwing up of rods in 36-foot lengths, and in a hole 1,000 or 1,500 feet deep the labor required is very great. Expert drillers can raise and lower the rods at the rate of 100 feet a minute, and ordinary workmen at the rate of 60 to 75 feet a minute.

In drilling some wells bailing does not occupy so large a part of the time. In artesian wells, for example, the cuttings may be carried away by the pressure of the water. The head at shallow depths may, however, be insufficient to accomplish this, but it may be greatly increased when the hole is deepened to coarser water-bearing material, and bailing may then be discontinued. In creviced rocks the drillings may be carried off by the downward and outward movement of the water.

When lowering the rods into the drill hole care should be taken to keep the lowest joint—that connecting the rods with the jars—looser than any of the other joints of the string, so that if the drill sticks fast in the rock the driller may unscrew the rods and remove them from the hole without difficulty.

The drill may then be loosened by a fishing spud and the rods lowered into the hole, fastened to the pin of the jars, and the tools withdrawn. Occasionally, however, the lowermost joint becomes tight, especially when drilling in rocks of irregular structure or rocks in which there are many crevices. In an accident following such a tightening of the rods on the drill it is sometimes necessary to lower a knife into the well and cut away the rods just above the drill. Then, after the tools have been spudded loose, they may be withdrawn by a slip socket.

Loss of tools—the most common accident in using pole-tool outfits—is due to failure of the man at the well head to catch the square shoulder at the end of the rod with his wrench, as a result of which the tools drop to the bottom of the well. The rods are usually broken by this accident and have to be removed piece by piece by means of spears, slip sockets, and other devices. Sometimes the buckling and breaking of the rods in the hole prevents their withdrawal and the hole must be abandoned.

A drill in a well in which the driller desires the water to enter from all parts of the hole may encounter caving rock between two water-bearing beds. An attempt to shut off the caving rock by casing from the surface to the rock would shut out the water above it or would necessitate perforating the casing at the level of the upper water. Caving is therefore prevented by lowering into the well a piece of casing long enough to cover the caving rock. The hole is then reduced in size and drilling is continued. In the vicinity of Chicago caving rock is found at a depth of about 1,000 feet. It does not usually carry much water and the little it contains is under slight head. The short piece of pipe, therefore, stops the inflow of material and allows drilling to proceed.

Where a pole-tool outfit encounters quicksands it is almost worthless because of the great amount of time required in withdrawing the tools and the rapid inflow of the sand, and it must therefore be supplemented by rotary appliances.

SELF-CLEANING OR HOLLOW-ROD METHOD.

OUTFIT.

The self-cleaning or hollow-rod method of well sinking includes the essential features of the percussion methods, but differs in combining in one operation the breaking up and removal of the material.

The tools consist of a string of pipe with screwed couplings, usually of special manufacture to insure strength and durability, with a water swivel at the upper end and a drill bit at the lower end. Because of this use of joints of pipe instead of a drilling cable the machine is often called the hollow-rod outfit.

The water swivel is essentially a swiveled gooseneck that allows the water and drillings to be discharged from the pipe in a constant direction and still permits the drill pipe to be rotated. In the usual outfits of this class the pipe is $1\frac{1}{2}$ or 2 inches in diameter and the drill is $2\frac{1}{2}$ to 4 inches across, though the hole may be enlarged by using an expansion bit.

The drill bit has one or more holes at its upper end and a flap valve that allows water and drillings to enter the pipe and be lifted automatically to the surface. Blind valves are also usually placed at intervals within the pipe to relieve the lower valve of the weight of the entire column of water and drillings.

The outfit usually includes a mast that is held upright by guy lines and supports a sheave pulley over which passes the cable used in operating the tools. In many of the outfits the device for lifting and dropping the tools consists simply of a pulley and reel. The cable is fastened to the upper end of the string of hollow rods, passed over the sheave pulley, and one or two turns are taken around a

hoisting reel. As the reel is continuously revolved by engine or other suitable power the drill may be raised and let drop by alternately tightening and loosening the rope on the reel. Self-cleaning tools are also commonly used with portable rigs, being operated by the spudding attachment.

The "Ohio" machine is a self-cleaning outfit that has been fitted with a special operating device. In this outfit the rods are gripped by jaws and lifted by power transmitted through a crank and pitman. At the upper end of the stroke levers attached to the jaws are tripped, the tools are released and fall freely, and are caught up again by the jaws, on the rebound of the blow.

DRILLING OPERATIONS.

In drilling by the self-cleaning method water must occasionally be poured into the well until it is encountered in sufficient quantity for the needs of drilling. The drilling operation is continuous, for as the drill is alternately raised and let fall the jumping or pumping action forces water and drillings into the drill rods and upward to the surface. This action resembles that of a hydraulic ram, but in the drill the sudden compression required to open the valve is obtained by the drop of the tools instead of by the fall of a water column, as in the ram.

The efficiency of the pumping action of the drill depends on the shape of the drill shoulder, which for best results should have a circular cross section a little smaller in diameter than the width of the flat cutting edge, from which it should flare outward sharply so as to obtain the greatest effects of compression in opening the valves and forcing the drillings upward.

The pipe is slowly rotated during drilling, so that the drill will not strike twice in the same place and so that it will spall the rock off in flakes and not break the material simply by striking a straight blow. Ordinary casing with screw couplings is commonly used to case off caving material and excessive water, and is sunk as drilling progresses by a drive weight attached to the drill rods, whose weight is thus made to aid in the driving.

A properly tempered bit will be sharper when it is taken out of the hole than when put in, for the wear comes mainly on its edge and tends to reduce its gauge. When the approximate depth of the hole to be drilled is known, bits may be run long distances. So long as they are larger than the joints on the rods they will not stick as will cable bits when worn, for the vibration of the rods keeps them free. Many holes 100 to 150 feet in depth have been drilled with one bit without removing it from the hole. When a bit is used too long, however, the hole must be reamed when a bit of standard gauge is substituted for it.

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USES.

The self-cleaning outfit is admirably adapted to sinking water wells of small diameter in sand, clay, shale, soft limestone, and other easily penetrated materials. Concerning its use for this purpose, Veatch says:[a]

> The important feature of this rig from a water standpoint and the one which makes it of peculiar utility for sinking water wells in the Coastal Plain region is that it is impossible to pass a water-bearing stratum, no matter how small, without being aware of its presence.

The self-cleaning drill is also used extensively in prospecting for coal in Ohio and for lead and zinc in Wisconsin and Illinois. In coal prospecting a solid drill and cable are often used in drilling much of the distance down to the coal bed, and the self-cleaning tools are then used to determine the thickness of the bed. A larger bit than common is usually employed for this purpose, as it takes larger and more determinative samples. The casing can be easily withdrawn from prospect holes by driving it upward.

CALIFORNIA OR STOVEPIPE METHOD.

INTRODUCTION.

For sinking water wells in the unconsolidated alluvial deposits of portions of California a method is used which, on account of its distinctive character, is called the California or stovepipe method. It is also sometimes called the mud-scow method, because of the instrument by which drilling and bailing are accomplished.

The following description is adapted from two articles by C. S. Slichter[b] and by I. N. Knapp.[c]

RIG.

The rig consists of a horizontal rectangular frame to which is hinged a derrick about 34 feet high, held vertical by two diagonal braces from the frame to the derrick. The walking beam—a marked feature of this rig—is carried at the top of the derrick. The bottom of the derrick is hinged to a saddle piece resting on two coiled car springs, which in turn rest on a heavy crosspiece bolted between the sides of the frame.

The hoisting reel and other machinery are placed on the framework just back of the derrick, and at the farther end are the engine

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[a] Veatch, A. C., Geology and underground-water resources of northern Louisiana and southern Arkansas: Prof. Paper U. S. Geol. Survey No. 46, 1906, p. 101.

[b] Slichter, Chas. S., Field measurements of the rate of movement of underground water: Water-Supply Paper U. S. Geol. Survey No. 140, 1905, pp. 98–103.

[c] Knapp, I. N., Drilling wells in soft and unconsolidated formations: Stevens Inst. Indicator, vol. 22, 1905, pp. 17–30.

and hydraulic pumps. When steam power is used, the boiler is separate and is placed at one side, near the engine. When the machine is to be moved, the mast is swung back on its hinges, with its

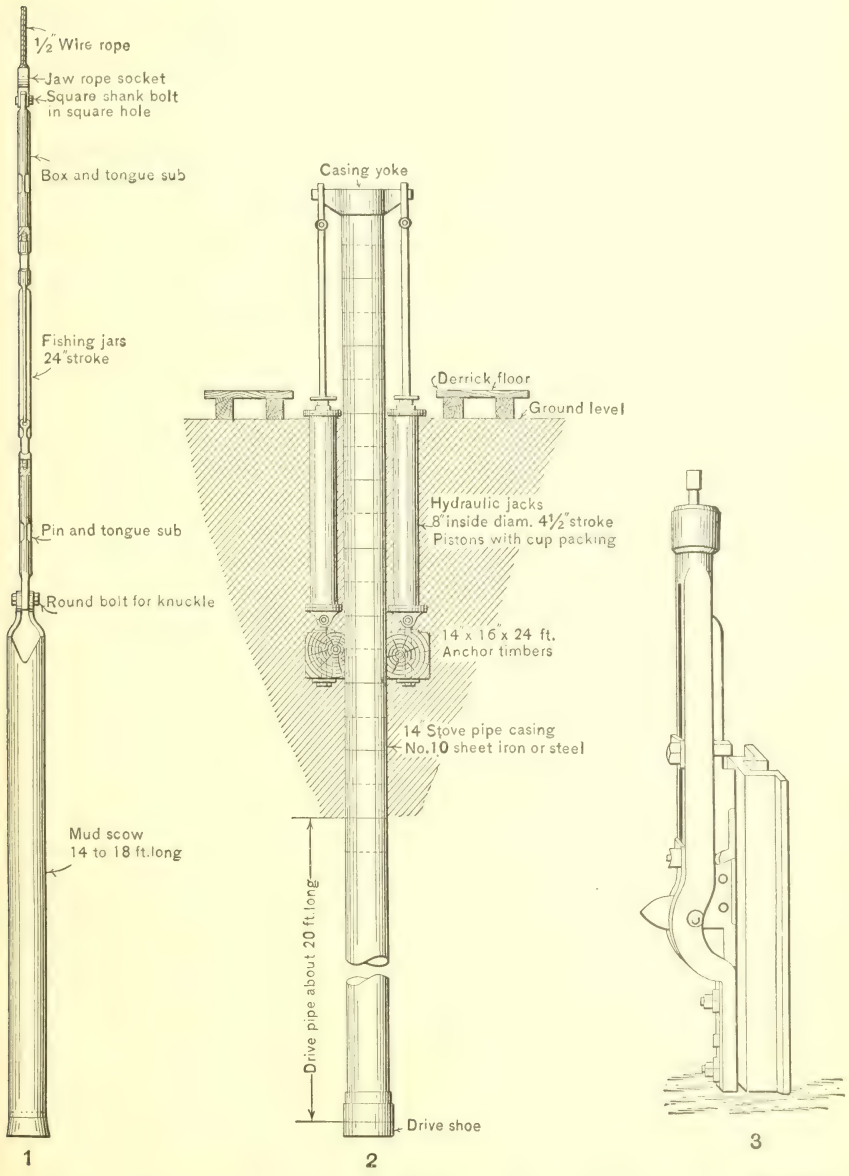

½" Wire rope
Jaw rope socket
Square shank bolt in square hole
Box and tongue sub
Fishing jars 24" stroke
Pin and tongue sub
Round bolt for knuckle
Mud scow 14 to 18 ft. long
Casing yoke
Derrick floor
Ground level
Hydraulic jacks 8" inside diam. 4½" stroke Pistons with cup packing
14 x 16" x 24 ft. Anchor timbers
14" Stove pipe casing No. 10 sheet iron or steel
Drive pipe about 20 ft. long
Drive shoe
1
2
3

FIGURE 12.—Parts of California or "stovepipe" outfit. 1, String of tools; 2, casing, drive shoe, etc.; 3, perforator for slitting stovepipe casing.

top resting on an upright at the rear end of the rig. Jackscrews are then placed under the sills and the whole machine is raised sufficiently to allow wheels to be slipped onto axles bolted to the sills.

In drilling, the walking beam is given a reciprocating motion by a wooden rod attached to its rear end and to the driving machinery. The tools are suspended from its forward end by a cable, usually a half-inch wire rope. The string of tools below the socket by which it is attached to the cable consists of a box and tongue sub, to which is screwed a pair of jars of the usual type, and below the jars is another sub to which is fastened the sand bucket or mud scow. (See fig. 12[1].) The sand bucket is similar in shape to that used with the standard outfit, and has a flap valve at the bottom, like that of the standard sand bucket; but it differs in being connected to the tools above by a knuckle joint that permits easy dumping, instead of by a bail, and at the bottom it carries a cutting shoe similar to that used on the bottom of a string of casing. For drilling in clay this shoe may be modified by a straight chisel-like bit extending as a diameter across it.

CASING.

The casing used in this method of drilling is made of lap-riveted cylinders of sheet iron or steel, usually of No. 10 to No. 14 gage, 24 inches long and 6 to 14 or 16 inches in diameter. (See fig. 12[2].) These short joints are known as stovepipe casing. The pieces of sheet metal may be taken to the field flat and riveted there, but usually the riveting is done at the shops and the ends are also turned square and true. Two sizes are used for the string of casing, one of which just slips within the other, so that the joints of one may be adjusted to fall midway between the joints of the other. The sections are added one at a time as sinking proceeds, each 2-foot joint adding only 1 foot to the length of the string, and the outer and inner sections are united simply by denting with a pick. This casing is water-tight, but for water wells it is not necessary that it should be.

Stovepipe casing may be started from a properly recessed drive shoe, but it is easier to begin a well straight and keep it plumb by using a starter, as with other casing. This starter is 15 or 20 feet long and may be made of sections of stovepipe casing, often of three thicknesses, riveted together, or of a joint of heavy lap-weld casing. At the lower end is an annular steel drive shoe. (See fig. 12[2].)

The casing is usually sunk by two or more hydraulic jacks which are buried in the ground and anchored to two timbers, about 14 inches square and 16 feet long, planked over and buried 8 or 10 feet deep. In the smaller sizes of shallower wells the casing is sometimes forced down by two steel I-beams or railroad rails, arranged as powerful levers.

DRILLING OPERATIONS.

After the outfit has been set up and the starter and hydraulic jacks have been sunk in position, the string of tools is lowered and drill-

ing begins. In this process the sand bucket or mud scow, as it is worked up and down by the walking beam, acts both as a drill and a bailer. In ordinary material it is rotated to loosen the sand and gravel from inside of the casing, and when it is drawn up to be emptied the bucket is manipulated in such a way that the weight of the jars and connections assist in the dumping.

The driller stands at the front of the rig and has complete control of the engine, hydraulic pump, jacks, and clutches that cause the tools to work up and down or be hoisted.

Water is necessary for the drilling operation, and must be added at the top of the casing until it is struck in the hole. The sand bucket must not be run until it is filled to overflowing, for the excavated material may spill over between the bucket and the casing and stones and gravel may become jammed between them and cause a serious fishing job. Bowlders that lie in the way are usually worked to one side of the casing shoe and passed by, by drilling on them with the bucket, which takes up the finer material; or if the bowlders are unusually difficult to pass, they are broken to pieces by a drill that is substituted for the sand bucket.

In drilling in quicksand or caving ground it is necessary to keep the water level about the same inside the casing as on the outside, and also to keep the casing even with or ahead of the excavation made by the bucket. In very soft ground a hole larger than the casing is apt to form, thus making a cavity outside of the casing, and falling ground from the top of such a cavity is liable to crush the casing.

PERFORATION OF CASING.

A record of the material encountered in sinking the well is kept, and after the well has been sunk to the required depth a cutting knife is lowered into it, and vertical slits are cut in the casing at such water-bearing strata as may be most advantageously drawn upon. A well 500 feet deep may have 400 feet of screen—that is, perforated casing—if the circumstances justify it.

One style of perforator for slitting stovepipe casing is shown in figure 12[3], the perforator being shown in cutting position with knife extended. It is handled with a 2-inch standard pipe with $\frac{3}{4}$-inch standard pipe inside. In going down and in coming out of the well the weight of the $\frac{3}{4}$-inch line of pipe holds the point of the knife up. When ready to "stick" the $\frac{3}{4}$-inch line is raised; then by raising slowly on the 2-inch line with the hydraulic jacks, cuts are made three-eighths of an inch wide and 6 to 12 inches long, according to the material at that particular depth. Another style of perforating knife has a revolving cutter that punches five holes at each revolution of the wheel. This kind of perforator is called a "rolling knife."

ADVANTAGES.

The advantages of the California method of well construction for use in unconsolidated deposits have been summarized by Slichter as follows:[a]

1. The absence of screw joints liable to break and give out.
2. The flush outer surface of the casing, without couplings to catch on bowlders or hang in clay.
3. The elastic character of the casing, permitting it to adjust itself in direction and otherwise to dangerous stresses, to obstacles, etc.
4. The absence of screen or perforation in any part of the casing when first put down, permitting the easy use of sand pump and the penetration of quicksand, etc., without loss of well.
5. The cheapness of large-size casings because made of riveted sheet steel.
6. The advantage of short sections, permitting use of hydraulic jacks in forcing into the ground.
7. The ability to perforate the casing at any level at pleasure is a decided advantage over other construction. Deep wells with much screen may thus be heavily drawn upon with little loss of suction head.
8. The character of the perforations made by the cutting knife are the best possible for the delivery of water and avoidance of clogging. The large side of the perforation is inward, so that the casing is not likely to clog with silt and débris.
9. The large size of casing possible in this system permits a well to be put down in bowlder wash where a common well could not possibly be driven.
10. The uniform pressure exerted by the hydraulic jacks is a great advantage in safety and in convenience and speed over any system that relies on the driving of the casing by a weight or ram.
11. The cost of construction is kept at a minimum by the limited amount of labor required to man the rig as well as by the good rate of progress possible in what would be considered in many places impossible material to drive in, and by the cheap form of casing.

HYDRAULIC ROTARY METHOD.

DEVELOPMENT.

The hydraulic rotary method of drilling has been used for many years for sinking shallow water wells in fine-textured, unconsolidated materials, but it attained prominence in deep-well drilling in 1901, when it was first successfully used in sinking oil wells in the Spindle Top field near Beaumont, Tex., where other methods of drilling had failed, and it has since been a great factor in the development of the Texas fields. Its successful use in that region and the consequent great improvement in the machinery employed has led to its increasing use where soft materials are encountered. Sinking is accomplished by the rotation of an annular toothed shoe on the bottom of the string of casing.

[a] Water-Supply Paper U. S. Geol. Survey No. 140, p. 101.

OUTFIT.

With the hydraulic rotary outfit a derrick similar to that of the standard rig is used, but the machinery and tools are unlike those of percussion outfits. The principal parts of the machinery are a revolving table or whirler, two hydraulic pumps, and boiler, engine, and line shaft to furnish power.

The revolving table is a heavy rotating device, set on tool-steel rollers, that grips the casing firmly and permits it to be revolved and yet allows it to be gradually lowered as sinking progresses. The table is revolved by means of bevel gearing connected with the line shaft and controlled by a clutch and lever.

The hydraulic pumps, which supply water for drilling, are capable of developing a pressure of 125 to 175 pounds to the square inch. As the water used is very muddy the pumps are made with but 6 to 10 valves, whereas if the water were clear 20 to 24 valves would be used. The valves also fit more loosely than in ordinary pumps, so as to reduce the abrasion produced by the sediment. Only one pump at a time is in use, but to permit packing of the valves and to provide for accidents and emergencies two pumps are always installed. In many plants two boilers are also installed for similar reasons. The pump that is in use is connected with the top of the casing through a hose line and water swivel similar to those in the self-cleaning outfit, but larger, so as to allow the continuous pumping of water into the casing while the latter is being rotated. A back-pressure valve is usually inserted in the gooseneck at the upper end of the swivel, to relieve pressure on the hose. Two swivels are needed, one being attached to the joint of casing to be next added to the string, while the other is in use.

The engine is connected by a link drive chain to the line shaft, which also furnishes power to the revolving table and to a hoisting drum and reel.

Thin mud or slush plays an important part in drilling, and a slush pit is an essential accessory of the outfit. This pit is usually dug near the derrick, on the same side as the pumps, and is about 40 feet long, 15 feet wide, and 3 or 4 feet deep, though the size varies with convenience and the preference of the driller. A ditch where sand may settle out of the mud is cut from the well circuitously to the slush pit, from which hose or pipes lead to the pumps. (See fig. 13.)

DRILLING OPERATIONS.

Drilling is accomplished by rotating the entire string of casing, on whose lower end is a toothed cutting shoe. The rotation under heavy pressure breaks off and grinds up particles of the material that

FIGURE 13.—Hydraulic rotary outfit; plan and elevation.

is being penetrated, and they are carried to the surface by water that is pumped down the casing under pressure and rises on the outside, between the casing and wall of the hole. Only one casing, that which is being revolved, is used, for as the muddy water escapes upward it puddles the side of the well so that the material stands alone.

If a bed of clay is encountered, the water used in drilling is kept as clear as possible and is not drawn from the slush pit, for the clearer the water is when introduced the greater is its capacity to uphold and move particles of earth, and the clay is sufficiently compact to make a wall that will not cave. In penetrating sand and gravel layers, clay often has to be added to the slush pit, so as to make a thin mud that will plaster up these beds and prevent them from caving and also prevent the escape of drill water into them. In some oil fields a trough with revolving paddles, called a mud mixer, is used to prepare the slush of proper consistency for plastering up sandy layers and also for closing gas pockets.

A pressure gage enables the driller to feed the casing into the hole with uniform pressure. The casing must be lowered with care, for if it is fed too fast the hole may become clogged by failure of the pumps to raise the outside column of water and carry up the drillings. Many clays are so compact and dry as to resist strongly the action of the water, and if the casing is fed too rapidly a core forms within it, reducing the size of the opening through which the water must pass, and correspondingly increasing the pressure exerted by the pumps. This difficulty may be obviated by fastening across the end of the rotary shoe a bar that will cut the core to pieces as rapidly as the shoe is fed into the clay.

When the casing has been sunk so that its top is near the revolving table, another length of casing to whose upper end the second water swivel is attached, is elevated by means of the hoisting reel so that it can be screwed onto the last length used. The first water swivel is then unscrewed, the new length of pipe is coupled on, and the hose connected to the water swivel at its upper end. This operation requires only a few seconds of the skillful workmen's time, and drilling proceeds with scarcely any interruption. To prevent the drenching of the men during the attachment of the water swivel, the pipe couplings are sometimes fitted with back-pressure valves.

It is essential that the pump be kept going constantly, otherwise the drillings will settle in the bottom of the hole and "freeze" the pipe fast. Should drilling cease at any time the water circulation must be kept up if possible, as slight cavings of material will cause the pipe to become clogged.

One size of casing is carried down until the friction of so much pipe against the wall of the hole renders its turning difficult, or it

becomes "frozen," or stuck fast, from some other cause. A smaller size is then used until it in turn becomes fast. When it does become necessary to withdraw the rotary casing to change a shoe or put in a well casing, the driller always risks a caving hole where the wall is not protected by casing; but if the wall of the hole is thoroughly puddled the risk is not great, and often one may see drillers in the oil regions of Texas pull 700 or 800 feet of casing, the whole section of loose sands and clays standing unsupported.

SPECIAL OPERATIONS.

In penetrating firm material it is sometimes necessary to employ a rotary drill bit instead of the rotary shoe. Two styles of bit for this purpose are in general use—the diamond-shaped and the fishtail. The diamond-shaped is usually first employed, and the fishtail afterwards used for reaming or enlarging the hole. These bits are used on a smaller casing than that which is employed with the rotary shoe, and slip down inside the larger casing. In hard rock chilled shot or other abrasive may be used as in the shot method, described on page 86.

For fishing operations, which are sometimes rendered necessary by the twisting off of the casing, tools are used that do not differ greatly from those employed for similar purposes in percussion drilling. If the twisted-off portion is short, however, it may be possible to pass it by using a diamond-shaped bit and "sidetracking" or drilling past it.

On completing an oil well by the rotary method it is best to withdraw the casing and replace the toothed rotary shoe by an ordinary drive shoe, for it is difficult to make a water-tight joint at the bottom if the toothed shoe is left in the well. As in the percussion methods of oil-well drilling, the drive shoe is usually set in the formation that is known from other wells in the same locality to overlie the oil-bearing sands. Drilling is then continued inside the casing for the remaining few feet or yards to the oil sands, and a smaller string of casing with a strainer at the bottom is lowered to the oil.

Packing is accomplished, as in other methods of drilling, by seed bags, cement, or special packers. A packer called a boot leg is also frequently used. This is a slightly tapering leather sleeve somewhat larger than the casing. It is slipped over the casing and its lower (smaller) end is tied fast to the casing a short distance above the strainer. The mud remaining about the casing settles into the open upper end of the boot leg and thus fills and packs the space between the casing and the side of the hole.

Many water wells sunk by the hydraulic rotary method are difficult to screen because of the depth at which the operation is conducted and the fineness of the material. A method in use is to puddle the

wall of the well at the water-bearing layer, set the screen, and draw the casing to the top of the screen. By pumping heavily for a few hours the pores of the puddled water-bearing sand are partly reopened, but the method has the defect of leaving the water-bearing layers more or less clogged by fine material. A more difficult but a better and more common way of screening is to sink the screen below the casing by forcing a hole down by a jet of water, the wash pipe being run ahead of it. A packer or lead seal is then inserted at the point where the top of the screen joins the well casing to prevent material from rising over the top of the screen and filling it.

ADVANTAGES AND DISADVANTAGES.

An objection to the hydraulic rotary method for drilling water wells has been made by some engineers, who claim that the driller often seals off water by puddling, and that the location of the water-bearing stratum must be known before drilling begins, otherwise it will be passed through without the driller being aware of its presence. But operators of hydraulic rotary outfits claim that it is very easy to tell when a water-bearing layer is reached, as the gage shows a sudden decrease of pressure. This is true if the head of the water encountered is considerably beneath the level of the surface, but if the head is close to the surface—that is, if the water is nearly if not quite artesian in the sense that it will flow at the surface—the pressure will remain nearly the same and it will be impossible to tell that a water-bearing layer has been encountered.

The hydraulic rotary method is very rapid for drilling in loose material where the drill may descend continually. At Corsicana, Tex., 1,065 feet were drilled through clay and marl in thirty-two hours. Both method and machinery have been rapidly developed through extensive use in the Texas oil fields, and as the method becomes better known it bids fair to supplant others in use for lighter jobs. The method will, however, never supplant the jetting and self-cleaning methods for shallow work where only a cheap, light rig is required, any more than the heavy standard oil-well outfit will supplant portable rigs for drilling shallow wells; but for wells about 1,000 feet deep, in soft, fine-grained materials, it will in time be almost exclusively employed, especially as the number of drillers who understand its operation is rapidly increasing.

JETTING METHOD.

OUTFIT.

In the jetting method of well sinking the material is both loosened and carried to the surface by water under pressure.

The principal parts of the outfit are a force pump and water swivel, drill pipe, nozzle or drill bit, casing and drive weight.

Hand-power jetting outfits are made in several styles which differ chiefly in the arrangement for driving the casing. One outfit uses a block and tackle for raising and letting drop a weight of 200 pounds or more; another uses a lighter weight which is lifted directly by hand. Some outfits require a light derrick and working platform; others are operated from the ground. In a light hand-power rig like that shown in figure 14 the casing is about 2½ inches in diameter and the drill pipe about 1 inch. The larger machines have a mast and hoisting sheave and use engine power for handling the casing and drive weight and for working the pump.

DRILLING OPERATIONS.

In the jetting method water is led into the well through a pipe of relatively small diameter and forced downward through the drill bit against the bottom of the hole. The stream of water loosens the material and the finer portion is carried upward and out of the hole by the ascending water current, as in the hydraulic rotary method. During drilling the drill pipe is turned slowly to insure a straight hole.

Casing is usually sunk as fast as drilling proceeds. In the softer materials, by using a paddy or expansion drill (fig. 14[4a–4b]) a hole may be made somewhat larger than the casing, which may be lowered a considerable distance by its own weight. Ordinarily, however, a drive weight is necessary to force it down. As a rule one size of casing may be employed for the entire depth of the well. It is usually difficult to drive a single string of casing beyond 500 or 600 feet by this method, and if the well is sunk much deeper, a smaller size must be used. In fine-textured, clayey or loamy material the hole may often be jetted down to the full depth required and the casing inserted afterwards, for the wall of the hole becomes puddled by the muddy water and the vibration of the drill pipe against it, so that it will stand alone, like the wall of a well drilled by the hydraulic rotary method.

When drilling with a light rig, hard layers may be penetrated by using a drill bit on the drill pipe, and raising and dropping the pipe so as to strike blows as in the percussion methods. In this operation a blind valve is usually inserted in the drill pipe near its bottom to prevent drillings from entering and clogging the pipe. With a heavier rig, equipped with mast and hoisting sheave, a cable and small drill may be used for penetrating locally hardened layers that do not readily yield to the water jet.

USES.

The jetting method affords a rapid and cheap means of sinking small water wells in comparatively fine-grained, unconsolidated ma-

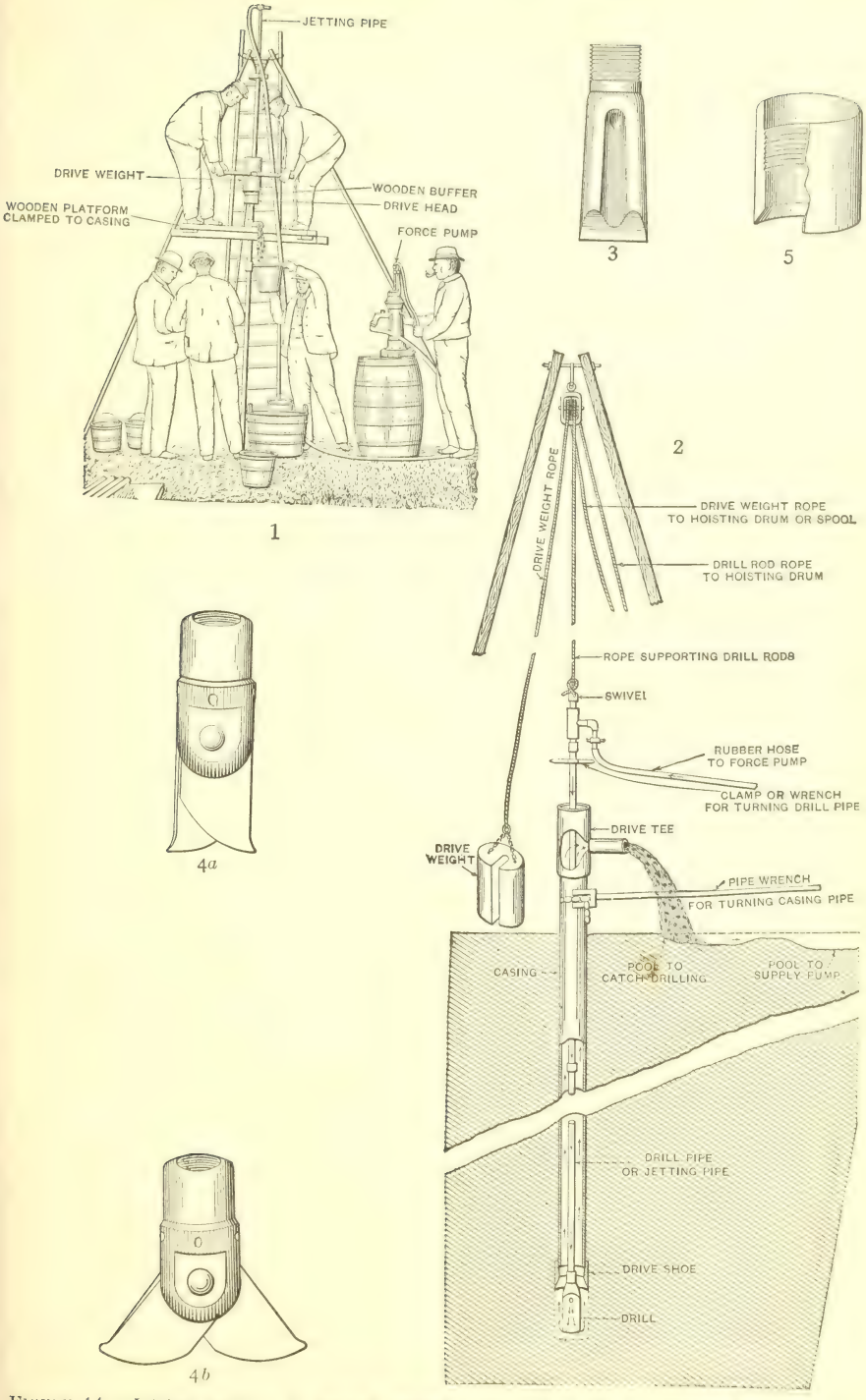


FIGURE 14.—Jetting outfit. 1, Simple jetting outfit; 2, jetting process; 3, common jetting drill; 4[a,b], paddy or expansion drills; 5, drive shoe.

terials and has the advantage of being easily taken from place to place. A fundamental disadvantage is that the nozzle or bit requires considerable water for its operation, and in some localities this requirement is a serious obstacle to the use of the method.

The jetting method is much employed for putting down wells in the Atlantic Coastal Plain and in some of the valleys of the arid West that are deeply filled with alluvium. In the Coachella Valley in southeastern California the method has been very successfully used in sinking wells for flowing artesian water. Most of the wells in this region are 400 to 500 feet deep and about 4 inches in diameter, and not uncommonly a well may be sunk, cased, and cleaned in two days.

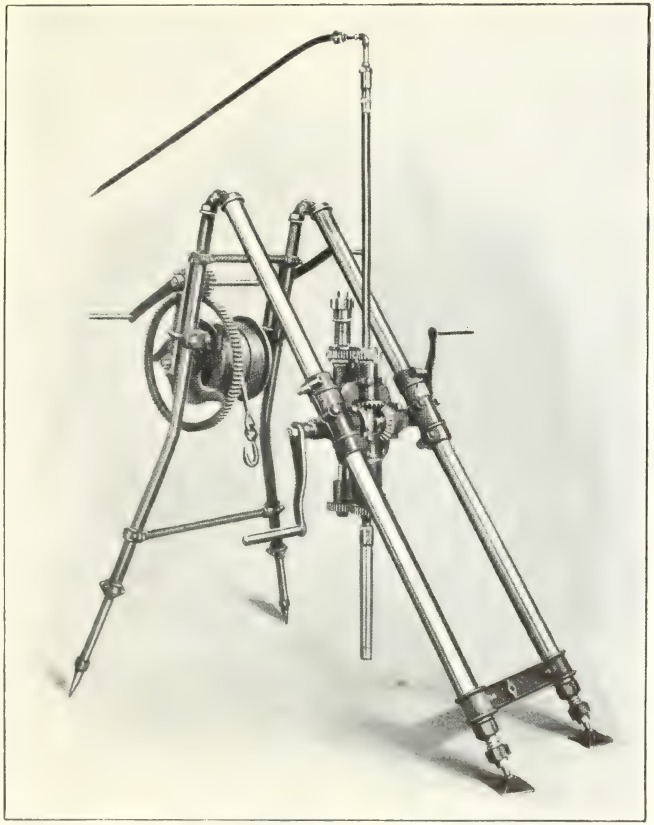
The method is also used in a few localities in mining kaolin. An iron pipe, 4 inches in diameter, is sunk to the clay bed, and inside this pipe a 1½-inch pipe, having a drill attached to its lower end, is inserted. A stream of water is forced down the pipe, loosens the clay, and forces it up between the smaller and larger pipes. By adjusting the pressure of the descending water column the coarser, impure materials in the clay bed are left in the bottom of the well, and only the finer material comes to the top. A very sharp fine-grained white sand is separated from the kaolin as a by-product in the washing and is used for masonry. All the clay within a radius of 40 feet of the hole and through the entire thickness of the bed is pumped to the surface in this way, and the pipes may then be pulled and used in another hole. The kaolin forms about 5 per cent of the solution forced to the surface, the fluid having the appearance of milk.

CORE DRILLING.

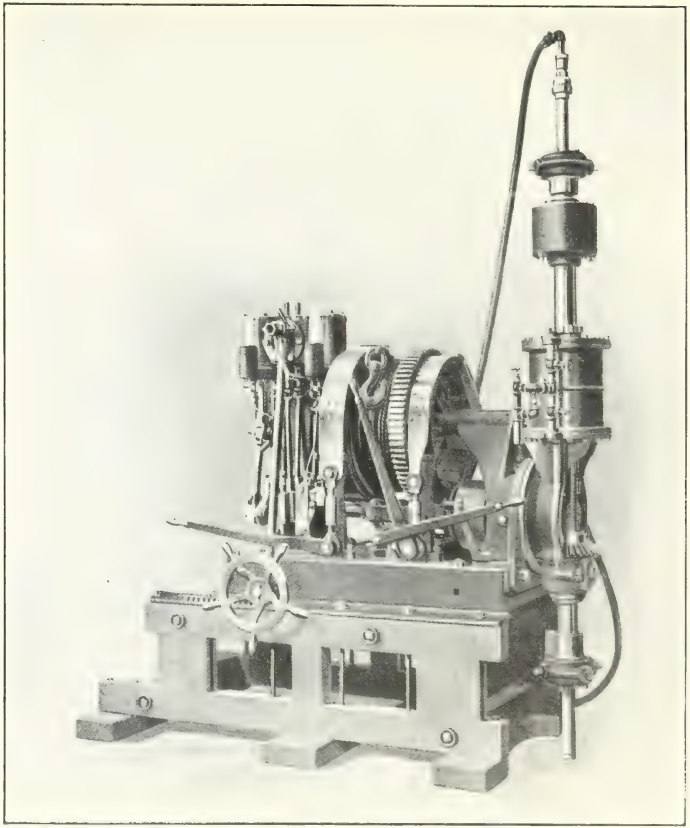
GENERAL FEATURES.

Core drills are little used for sinking wells, though they have been tried from time to time in developing new oil fields, and diamond drills have been employed to some extent in South Africa for deep-water wells. The core-drill principle is, however, occasionally employed in connection with the more common well-drilling outfits.

The advantage of core drills over all other types of boring machines is that they enable an accurate sample of the material penetrated to be obtained. They are therefore widely used in prospecting for coal and other economic deposits, for making borings for foundations for dams and similar structures, in preliminary tunnel investigations, and in excavation work. The importance of obtaining a true sample of the material penetrated is illustrated by the experience of a firm of contractors, who became bankrupt because at a certain depth they encountered hard conglomerate, instead of the gravel indicated by the drillings of a percussion outfit.



A. HAND POWER DIAMOND DRILL, WITH FRICTION FEED.



B. STEAM POWER DIAMOND DRILL, WITH HYDRAULIC FEED.

Rotary core drills of the several classes are alike in employing a hollow rotary drill that by abrasion wears an annular hole, leaving a core in the center. The drillings are removed continuously by water under pressure, and the core is broken off and removed from time to time.

Core drills are intended primarily for drilling holes of relatively small diameter in hard material. They resemble hydraulic rotary outfits in method of operation, but the formation of a core and the necessity for its occasional removal makes the drilling process intermittent instead of continuous.

Core drills may be used in all kinds of rock, from the hardest trap to the softest shale, but where a core is not especially desired drilling in the softer formations can usually be done more rapidly by means of percussion, hydraulic rotary, jetting, or some other method, and as a rule saving can also be effected in the cost of outfit. A percussion core drill is described on page 59.

DIAMOND DRILL.

OUTFIT.

Diamonds were first used in drilling rock in 1863 by Rudolph Leschot, a French civil engineer. For deep-well drilling they were first employed by M. C. Bullock, who sank a hole to a depth of 750 feet in Schuylkill County, Pa., to determine the existence and thickness of coal beds.

Diamond-drill machines (see Pl. III, *A*) to be worked by hand are made, but the larger outfits (Pl. III, *B*) require a derrick, hoisting sheave, and hoisting drum similar to those employed in other methods of drilling. The drilling apparatus includes a force pump and water swivel, drill rods, and rotating device for turning them, feed mechanism, and a cutting bit.

The derrick in most common use is a tripod from 20 to 80 feet high, the height varying with the work to be done. Where timber is easily available the derrick may be constructed of poles, but for drilling to depths of 1,000 feet or more a strongly braced 4-pole tower or a steel derrick is usually employed. The drill rods are smaller and lighter than those used with the hydraulic rotary outfit, and the hoisting drum, force pump, and water swivel, though similar, are correspondingly lighter and are of somewhat different design. Only one force pump is installed, as the danger of sticking if the water current is stopped is not so great as in the hydraulic rotary method. The drill rods are of heavy lap-welded iron tubing or of seamless steel tubing, with screw joints (fig. 15[1 2]), and are 5 to 10 feet long. The sections are added as sinking progresses.

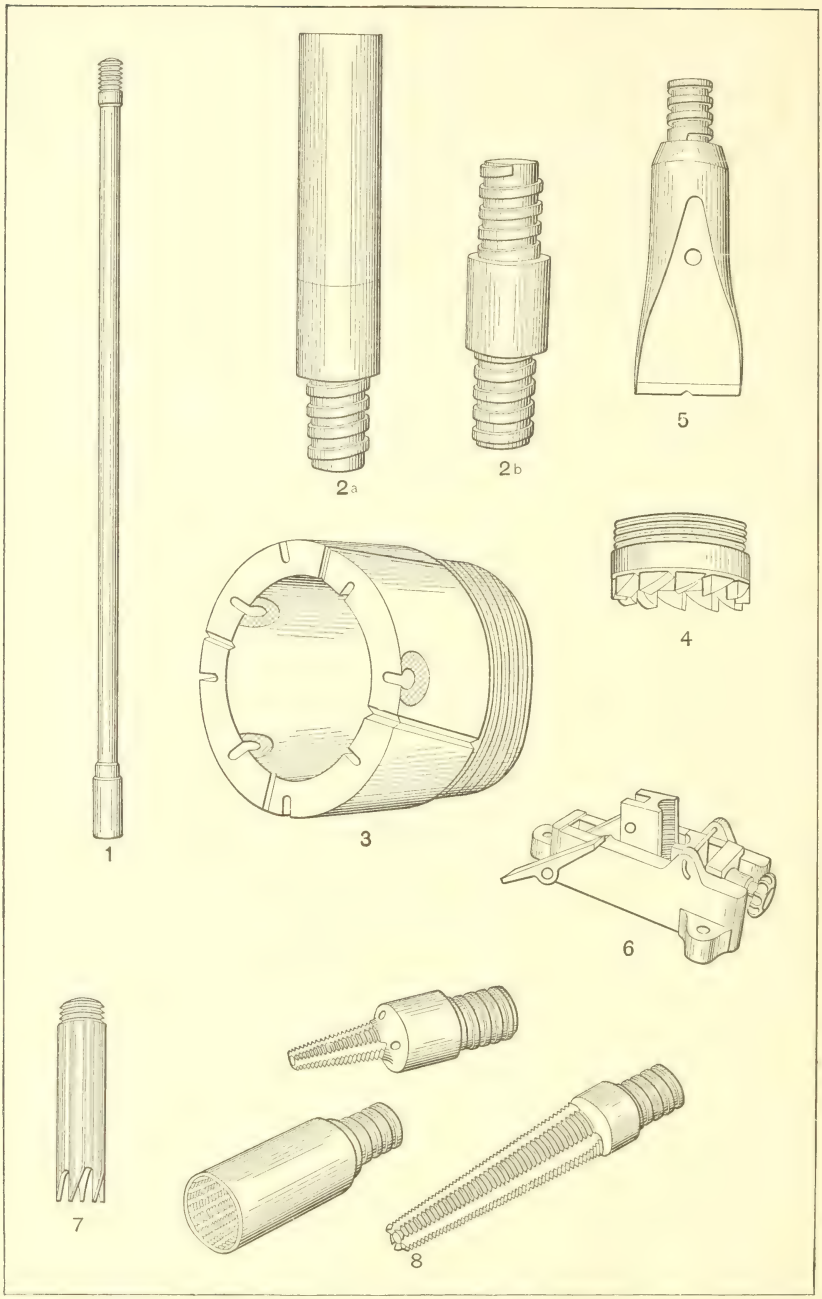


FIGURE 15.—Parts of core-drilling outfit. 1, Davis calyx drill rod with coupling attached; 2a,b, end of a drill rod and rod coupling; 3, bit to be set with diamonds; 4, toothed cutter bit; 5, chopping bit; 6, safety clamp; 7, toothed collar; 8, coupling recovery taps.

In nearly all diamond-drill outfits the drill rods are rotated by means of bevel gears. In the smaller machines connection with the power is made also by "tight" gearing, either chain or cog drive; but in the larger machine belt drive is used, so that the belt may slip if the drills become caught, as otherwise the rods may be twisted or broken.

As the total weight of the rods in a deep bore may reach 15 or 20 tons—a weight which would crush or break the diamonds—the rods must be supported and the drill must be fed into the rock slowly. Two feed devices—a differential feed and a hydraulic feed—are in general use, both designed to prevent the sudden and severe strain that would be brought upon the stones by drilling through soft and into hard rock with a positive feed—that is, a feed so regulated as to advance the drill rods equal distances in equal periods of time. In one style of differential feed used on many of the smaller diamond drills the drill rods are advanced by means of a frictional gear on the bottom of the feed shaft, which, by maintaining a uniform pressure on the drill, makes it sensitive to the character of the rock through which it is passing. A differential feed used on one style of calyx core drill advances the rods by a loop of rope which passes over a pressure yoke and is wound on two small drums.

In the hydraulic feed the forward motion is accomplished and regulated by means of hydraulic pressure which is applied through a cylinder and piston. The cylinder is connected to the pump which supplies water for drilling, and a pressure gauge indicates the amount of pressure on the bit. This device is under the immediate control of the operator, who regulates the feed by a small lever. The cylinder is so constructed that the water can not escape from its bottom faster than it enters at its top, and its lower part therefore always contains water. If a cavity is struck the drill rods hang on the piston, which is supported by the water, and as this is incompressible it prevents the rods from dropping into the cavity and the feed continues downward as regularly as if the drill were working in hard rock. Before the hydraulic feed was devised the diamond drill did not work satisfactorily in creviced rock because the drill and rods were apt to drop into cavities and thus break the diamonds.

The bit is made of a ring or sleeve of tough but ductile steel, three-eighths to five-eighths inch thick, whose upper end is threaded to screw into the drill rods and whose lower end is turned true and bored with eight holes to contain the diamonds. The diamonds are carefully set in the holes so that their lowest points lie in a plane, and are arranged alternately on the inner and outer faces of the bit, so that the outer edges of four project a little beyond the outer face and give it clearance, while the edges of the inner four project slightly beyond the inner face and clear the drill of the core. The diamonds

are calked in place by carefully swaging the steel firmly against them with light blows. The old method of setting was to drill into the bit a hole about the size of the diamond, insert the diamond, fill around it with copper or other malleable metal, and swage the stone in firmly; but this method was troublesome and the diamond was often broken. In the latest styles of diamond drill bit the diamonds are set in steel nibs which are soldered or brazed into their places in the bits. When these nibs are used the expert diamond setter's services may be dispensed with.

Care must be taken that the bottom tips of the stones lie in a common horizontal plane and their outermost tips in the circumference of a circle; otherwise drilling will be done only by those diamonds that project downward or outward the farthest. This might result in drilling a hole of irregular shape and considerable inclination, or it might result in failure to drill at all. Grooves are cut across the face of the bit between the diamonds, and also on its outer side to permit the passage of drill water. A bit ready to be set with diamonds is shown in figure 15[3].

The shape of the bit and arrangement of the diamonds permit the stones to cut a path for the drill and slightly enlarge the cavity around it, and this clearance allows the drill to be easily lowered into the hole and also gives passage between the rods and wall of the hole for the drill water to convey the drillings to the surface. The stream of water also keeps the bit cool and prevents injury to the diamonds by heating.

Two kinds of diamonds, known as carbons and borts, are used in diamond-drill work. Carbons are found as opaque, irregularly shaped nodules, black on the outside and shades of gray on broken surfaces. They have no cleavage planes, and it is this quality, together with their hardness, which especially fits them for drilling in hard rock. Borts are semitransparent diamonds similar in appearance to the rough brilliant but differing in crystallization. They are usually nearly spherical in shape, are as hard as carbons but not as tough, and have a cleavage plane, so that when used in hard rock they may break; whereas carbons wear away but seldom break. Carbons come mainly from Brazil; borts from both Brazil and South Africa. Borts are much cheaper than carbons and may be used in boring in soft rock. In some holes a toothed cutter bit (fig. 15[4]) similar to that of the hydraulic rotary outfit is used in penetrating soft rock. In moderately hard material a drill armed half with carbons and half with bort may be used, but for drilling in very hard rock only carbons are suitable.

The diamonds for a bit must be selected with special attention to uniformity of size and weight, as irregularity in this respect will

disturb the balance of stones and necessitate frequent resetting. They usually require resetting after eight to twelve hours' work, so that two bits are needed, or, if running continuously, three are often employed, so that drilling need not be suspended while the stones are being set. The size of diamonds used for drilling ranges from about 1 to 4 carats, according to the size of the bit. Stones of approximately cubical shape are best, as they are stronger and furnish better cutting faces.

In the early drills the core was removed by means of gravel dropped down the rods. This became tightly wedged between the core and rotating barrel and caused the former to be broken off and held tightly so that it could be brought to the surface. In present forms of the drill a core lifter is placed in the barrel a short distance above the bit. Commonly this device consists essentially of a core barrel or shell and a split ring or sleeve. (See fig. 16.) The shell is bored with a slight taper downward, and within it the split ring is placed. This ring is usually wedge-shaped and often has inward projecting lugs to grip the core. Because of its tapering shape the ring is loose when in the upper part of the shell, but when it is pressed toward the bottom of the shell it becomes wedged under heavy compression and grips the core tightly. While the bit is in motion the ring does not rotate, but rides lightly on the core, sliding down over it as the bit advances into the rock. When the "run" has been made and the tools are hoisted, the raising of the shell compresses the ring and causes it to grip the core, thus breaking it off close to the bottom and bringing it to the surface. In a core barrel of this type the wash water is forced downward between the core and the barrel, and when penetrating soft materials, as coal beds, the water may disintegrate the core and render the sample imperfect. The barrel also vibrates more or less and may cause the split ring to rub on the core so as to abrade it to some extent. In prospecting coal beds it is therefore customary to use a double core barrel which contains a tube that slides down over the core as fast as cutting proceeds and protects it from wear.

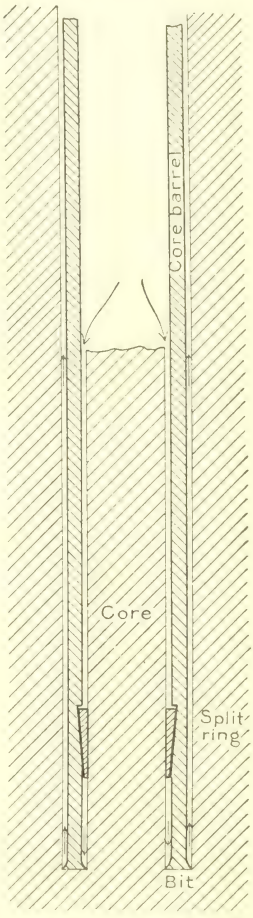


FIGURE 16.—Plain core barrel.

DRILLING OPERATIONS.

In starting a hole with a diamond drill the first requirement is to get down to rock. If the soil is thin, a pit is dug through it, a drive pipe is inserted, and a tight-fitting joint is made by chiseling out a seat in the rock, driving the pipe down and calking it firmly. If the soil covering is more than 10 or 12 feet deep, it is cheaper to drive the pipe to rock than to dig a pit for it. In places where the drive-pipe can not be set into the rock with sufficient firmness to keep out the surface water a hole is drilled inside the drivepipe with a chopping bit (fig. 15[5]) attached to the drill rods and a string of casing is put down to a depth sufficient to exclude the water.

When ready to begin drilling the drill spindle is set to the angle desired for the hole, a bit and core barrel are screwed to the lower end of a joint of drill rods, and other rods are added so as to bring the bit to the rock. The upper length of rod is then clamped in the spindle, so that the bit is a little above the rock, and the water swivel is screwed to the top of the rods and connected with the pump. The pump is then started, and when the return water begins to flow from the top of the casing the drill is started and the bit is slowly run down to rock. If the rock surface is not smooth, the bit will at first drill only one side, but soon all of the diamonds are cutting the rock, or, as the driller puts it, the drill has an "even bearing."

When the drill has been run into the rock the length of the core barrel drilling is stopped, but the pump is kept running long enough to wash all cuttings to the surface. A hoisting plug is then substituted for the water swivel and the line of rods is hoisted until the first drill-rod coupling is just above the safety clamp. (See fig. 15[6].) This clamp allows the rods to be hoisted, but grips them and guards against their loss by slipping downward and dropping into the hole. The top joint of rod is then unscrewed and passed out through the hollow spindle, the hoisting plug is lowered and screwed into the second length of the drill rods, and the line of rods is hoisted another length. Each joint in turn is removed until the core barrel reaches the surface, and the core is then taken out. By reversing the process the rods are again lowered into the hole, the water swivel is connected, and drilling is begun on the next "run."

CALYX DRILL.

DEVELOPMENT.

In 1873, shortly after Leschot first used diamonds for boring, large black diamonds of good quality could be purchased for $8 to $12 a carat; but since the introduction of the diamond drill they have advanced greatly in cost, and in 1910 were valued at $85 a carat for

a two-carat stone or $50 for a one-carat stone. Borts are much cheaper; the rate in 1910 was about $18 a carat. As carbons weighing 1 to 4 carats apiece are used in diamond drilling, the price of a bit set up ready for drilling is a large part of the initial cost. For prospect work this cost has been somewhat reduced by decreasing the size of the bore hole, but for water wells the diameter can not be reduced to less than about 2 inches, and even this reduction in the size of the bit causes the drill rods to turn on so sharp a curve as notably to increase the difficulty of drilling and the probability of accident.

On account of the increase in the cost of diamonds determined efforts have been made by engineers throughout the world to discover some method of coring rock without diamonds. Various hard substances, such as corundum, chrome iron, chopped steel, and garnet, and many varieties and forms of material have been tried unsuccessfully, attempt even being made to grind the rock by means of a free abrasive, such as steel filings, fed down the bore hole. Bits were also made of the hardest metals, and it was due to experiment along this line that the calyx drill was invented in Australia. It is now in use in many parts of the world.

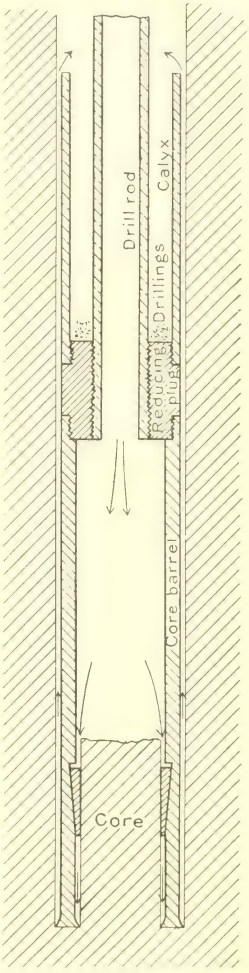


FIGURE 17.—Calyx core barrel.

DESCRIPTION.

The hoisting and driving machinery of the calyx drill is similar to that of the diamond drill, and feed water is supplied through a swivel and hollow drill rods. The bit of the calyx drill is made of hardened tool steel and consists of a toothed collar, somewhat like the cutting shoe of the hydraulic rotary outfit, but having longer barrel and teeth (see fig. 15[7]), the teeth being so set as to provide clearance to the core and to the bit and rods.

Above the core barrel a cylindrical chamber or calyx, open at the top, encircles the drill rods (fig. 17). Into it the coarser rock fragments torn off by the drill bit are caught as they are dropped by the upward water current when its velocity decreases. They are removed when the rods are hoisted to remove the core, and furnish a second record, in inverted order, of the materials penetrated. This record is of especial value in material too soft to yield a good core.

The action of the toothed bit in cutting the rock seems to depend largely on the torsional power of the drill rods, for the drill bites into the rock and resists turning until the twist of the rods forces it loose and partly around to a new grip. It thus has a "chatter" motion, which chips off fragments of the rock. Its action has been compared to that of the stone mason's chisel, which chips off rock fragments at each blow of the hammer.

The calyx drill is not restricted in size by such considerations of cost as is the diamond drill, and machines are built capable of taking cores 15 inches in diameter.

CHILLED SHOT METHOD.

Experiments in drilling by the use of loose abrasives poured down the drill hole led to the adoption for this purpose of chilled steel shot, such as is used in sawing marble and other stone. Other parts of the shot outfit are similar to those of the diamond drill, but cutting is accomplished by revolving an iron or steel tube on the shot. A slot a few inches long and half an inch wide cut into the lower end of the tube or bit allows the shot to reach the cutting surface more readily and be more evenly distributed. Distribution is also aided by slightly beveling the edges of the tube so that the shot may get under it. Under the weight of the drill rods the shot bites into the rock and chips out or wears off small pieces of it, which are brought to the surface by the water current.

That the supposedly round and smooth shot can thus wear away rock may seem at first almost impossible, but close examination of the tiny steel balls shows that they are slightly irregular in shape, and because of this unevenness of form they sink into the softer bit tube and are held firmly by it, abrading the rock surface as sandpaper abrades wood. The shot has no tendency to polish the hard rock—a tendency sometimes shown by the diamonds used in the diamond drill.

ACCIDENTS AND DIFFICULTIES IN CORE DRILLING.

The most frequent accident in rotary core drilling is the loss of rods through leakage. To recover them a screw tap may be employed, being lowered into the top of the rods, where it cuts its own thread, and thus obtains a firm grip. Taps (see fig. 15[8]) are made in various sizes and are used to recover casing, pipe, and core barrels, as well as drill rods. If the rod of pipe is bent so that a tap can not be used at first, the upper portion may be cut away with a reamer until the tap can be inserted. The position and condition of broken parts

may be ascertained, as in other drilling methods, by examining the lower end of the recovered portion, by using a mirror or by employing soap to obtain an impression of the upper part of the tools.

In using the diamond drill in formations containing hard pebbles or nodules loosely embedded in softer material the diamonds may be torn out and their recovery may be difficult. One device used to recover them is a ball of beeswax attached to the end of the rods.

Creviced rock offers difficulties to all core drills because of the uneven bearing it affords to the bit, and hence its tendency to deflect the hole. Crevices also cause loss of feed water and also of shot, when it is employed. These losses may perhaps be stopped by pouring into the hole oats, bran, sawdust, or other material that will swell under the action of water and fill the crevices. Care must be taken, however, that this material does not pack around the bit and prevent its withdrawal.

COMPARISON OF CORE-DRILLING METHODS.

The diamond drill is especially adapted to penetrate hard rock to great depths, and will bore a hole at any angle; hence it is especially useful in mineral-prospect work. It is somewhat restricted by the rock formation, however; for example, no diamond-drilling firm will send a drill into the lead and zinc districts near Joplin, Mo., for the limestone there contains many chert nodules, loosely embedded, which tear out the diamonds. In highly inclined and flinty rocks there is also danger of loss of the stones. The high cost of diamonds limits the use of this drill to boring holes of small diameter, and hence to the higher classes of work, such as prospecting for ore deposits.

The calyx drill is commonly used to bore much larger holes than the diamond drill, and in soft or moderately hard material it is cheaper. In very hard rock it works more slowly, however, and it is not adapted to boring holes at an angle greater than about 45° from the vertical. It is largely employed in coal prospecting and in boring holes for testing foundations.

The shot method may also be used in obtaining cores of large diameter. In very hard material it is more efficient than the calyx cutter, but it is not adapted to soft material. It may be used for boring holes at any angle, provided the drill is rotated rapidly and the shot kept properly distributed by centrifugal force.

All rotary core drills are portable and, as they can be taken apart for transportation on pack animals, can be used in regions where more cumbersome outfits are debarred. Nearly any power can be used—electricity, compressed air, steam, gasoline, horse, or hand—but where its use is possible steam is usually the best.

The three methods of rotary coring are sometimes used in boring the same hole, the style of cutting bit employed depending on the character of the material that is being penetrated. The shot and calyx bits are frequently interchanged, and on one of the leading makes of core drill the outfit is expressly designed to use a toothed cutter bit in soft and moderately hard rock and shot in penetrating the hardest materials. For this purpose a double water swivel is used, through one neck of which the shot is fed into the rods.

The percussion core drill (see p. 59) should prove valuable in sampling coal beds and in other work in comparatively soft formations in localities where a cable rig can be advantageously set up.

MINOR METHODS OF WELL SINKING.

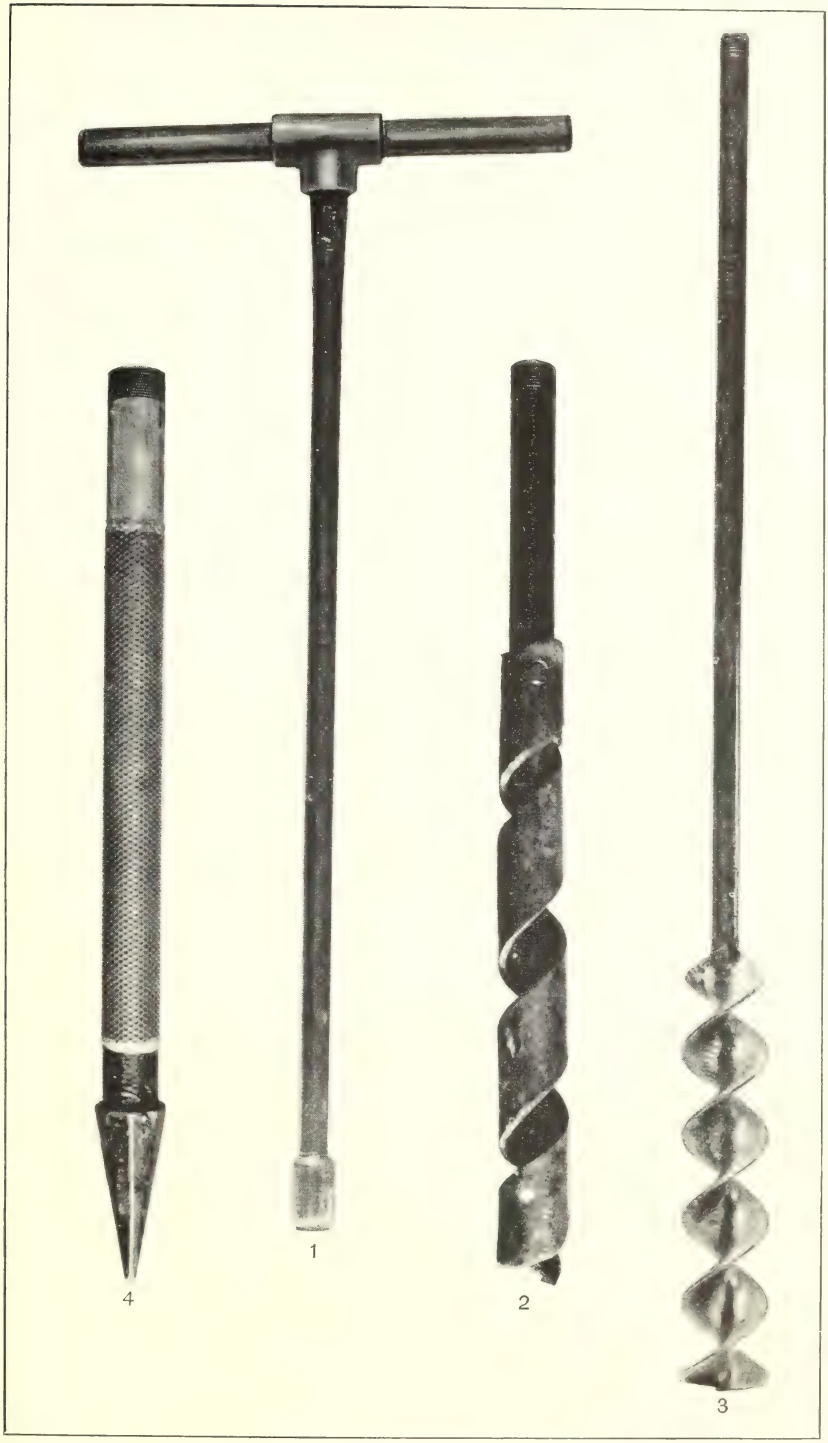
BORING.

In alluvial deposits along streams and in other unconsolidated deposits of gravel, sand, and clay wells 2 or 3 inches in diameter are in some parts of the country bored to the ground-water level with a hand auger made by welding a carpenter's auger to a rod or pipe. The auger works more efficiently if the centering point is cut off and the lips are shaped as shown in Plate IV, 3. A wrench formed of a plumber's tee and two short pieces of pipe may be used to screw the auger into the earth and pull it out with its load of material, and the rod may be lengthened by adding other sections of pipe as sinking progresses. (Pl. IV, 1.)

Another much-used type of auger is formed by making a spiral coil of tire iron, shaping a cutting bit on its lower end, and welding or riveting the auger thus formed to a joint of rod or pipe. (Pl. IV, 2.) Where the depth to water is not more than 25 feet these small augers may be fastened to a section of pipe long enough to reach to water. As the auger is heavy when loaded with material, a windlass or a small derrick with pulley blocks may be used in lifting it, and a platform may also be built from which the auger can be steadied and turned. In boring through dry sand or other loose deposits a little water should be poured into the hole to cause the material to cling to the auger.

Small wells bored with augers are adapted mainly to localities where the water level stands above the suction limit, for the hole usually bored is not large enough to admit a pump cylinder. The best suction pumps will raise water to the surface from a depth of about 28 feet.

To complete these shallow wells, a pipe 1½ or 2 inches in diameter, with a suction or pitcher pump (fig. 18 [5]) screwed to its upper end, is inserted to a point a short distance below the water level. In



1. SMALL EARTH AUGER; 2, 3. EARTH-AUGER BITS, 4. DRIVE POINT AND SCREEN.

relatively coarse material a natural strainer is soon formed about the lower end of the pipe by pumping out the finer sand, and it is usual

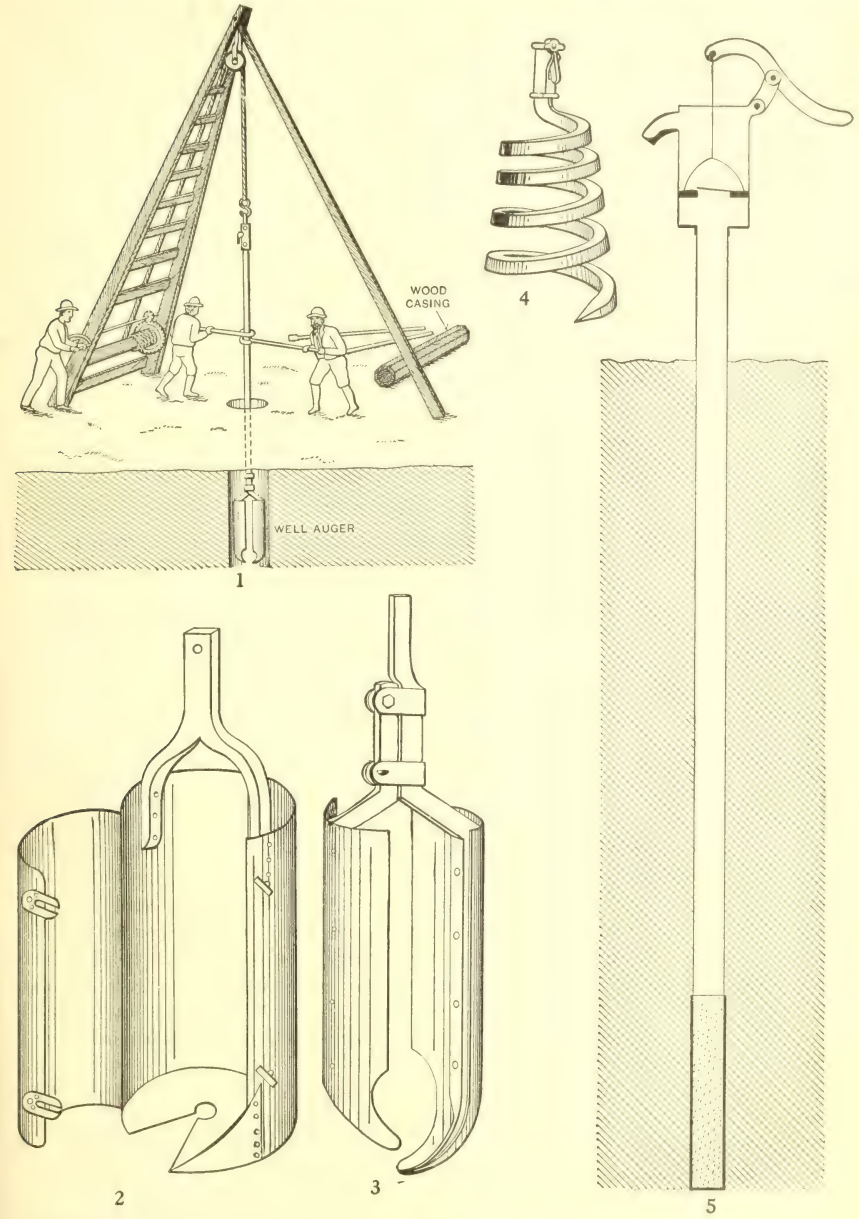


FIGURE 18.—Well-boring tools. 1, Ordinary well-boring outfit; 2, 3, well-boring augurs; 4, special auger for penetrating bowlders or rock; 5, suction pump.

to drill a number of small holes along the lower part of the pipe to aid in admitting the water. In finer material a screen is used to prevent the well from becoming clogged.

For boring wells of larger diameter augers of other forms are used, and correspondingly heavier apparatus is employed for turning and raising them. Different shapes of auger are employed for penetrating different materials. Two common shapes are illustrated in figure 18[2–3]. The larger augers range in diameter from 3 to 36 inches.

Casing is not usually required until the auger reaches saturated sands. Its use is then necessary to prevent caving and it may be driven down by a wooden maul or ram. Mud and water-saturated sand may be bailed out with a sand bucket, which in the smaller machines is handled with wooden rods instead of a cable, as the rods enable it to be more easily pushed down into the soft material at the bottom of the hole. Hard layers of material may be penetrated by substituting for the auger a drill similar to that used with percussion outfits. It may be operated by hand, in connection with a drum and sheave, as in the self-cleaning method.

In regions where the formation is clayey and holds together well an auger of different shape has been devised and is employed for sinking wells several hundred feet in depth. It is used especially in the lower Mississippi Valley and is known as the Arkansas clay auger. The following description of this outfit is taken from a paper by A. C. Veatch:[a]

> The auger is 15 feet long. It consists of an auger barrel 4 feet long, which is made of cast steel, and resembles a 3-inch pipe sawed vertically in half. This is fastened by a flat piece of iron to a second auger barrel, 1½ to 2 feet long; above this is a second piece of flat iron, square at the top and cut with threads for fastening to the wooden poles. At the bottom of the auger barrel, on the right-hand side, is riveted a steel-cutting edge. * * * This is commonly called the cutting bit, and projects inward 1¼ inches. On the opposite side and slightly above, is the "auger lip," which helps to hold the dirt in the auger barrel when the tools are lifted. In operation the auger is fastened to a short 10-foot pole known as the auger pole, and this to the regulation 26-foot pole. The tools are turned with a clamp, and when the bit begins to choke, the tools are lifted and dropped by means of a windlass. This operation jumps the dirt up in the bit, and so frees the lower end; it is termed "making a slip." If the clay is very dry a little water is added, and with the very sticky Cretaceous clay this process can be continued until the whole length of the auger is filled with a cylinder of mud. This 15 feet of mud represents about 10 feet in depth. Usually, however, the auger is filled for only about 10 feet, representing 7 feet of depth, before lifting the tools.
>
> When rock is encountered, a bar drill is used. This is sometimes attached directly to the wooden poles and sometimes to iron poles. * * *
>
> When sandy layers are encountered, which will not hold in the auger, the sand pump is used or enough clay is dumped in the hole to make the sand stick together.
>
> In cases where wells of larger diameter are desired, or where it is necessary to enlarge the upper part of the hole for wooden casing, the 3 or 3½ inch hole made with the Arkansas clay auger is enlarged with a reamer.

[a] Veatch, A. C., Geology and underground water resources of northern Louisiana and southern Arkansas. Prof. Paper U. S. Geol. Survey No. 46, 1906, pp. 95, 97.

PUNCHING.

In a few localities where the material is very clayey wells are sunk by a punch instead of an auger. Of this method and its use in Arkansas and Louisiana Veatch says:[a]

> In regions where there are uniform clay beds without rocks or bowlders wells are often made with a well punch. This consists of a cylinder of steel or iron 1 to 2 feet long, split along one side and slightly spread. The lower portion is very slightly expanded, sharpened, and tempered into a cutting edge. In use it is attached to a rope or wooden poles and lifted and dropped in the hole by means of a rope given a few turns around a windlass or drum. By this process the material is forced up into the bit, slightly springs it, and so is held. When the bit is filled it is raised to the surface and emptied. When working in very dry clay water is sometimes added to aid the bit in "picking up" the material. Thin sand layers are passed by throwing clay into the well and mixing it with the sand until the bit will take it up.
>
> This process is not very extensively used in this region, and is not so practicable as the Arkansas clay auger.

DRIVING.

Where the water level is within the suction limit of about 25 to 30 feet below the surface and the water-bearing beds are unconsolidated, small water supplies may be cheaply obtained by wells sunk by driving into the ground a strainer and drive point fastened to a piece of pipe. Other lengths of pipe are added and driving is continued until the strainer reaches a water-bearing layer.

Unless the depth at which water can be obtained is previously known, the well is tested from time to time by a suction pump screwed to the upper end of the pipe. When desirable water is reached the well is pumped rapidly for some time to free the strainer from particles of sand and clay. The coarser material adjacent to the strainer is thus washed free of sand and forms a natural filter at the bottom of the well. One style of drive point and screen is shown in Plate IV, 4.

The pipe may be 1 inch to 3 inches in diameter, and is usually driven into the ground by a wooden or iron maul, which may be manipulated by hand. Often, however, a heavy weight is used, operated by a revolving drum and hoisting sheave, as in the self-cleaning method (p. 64), or by horsepower devices of various styles. The greatest difficulty encountered in driving wells is in striking rocks. Unless the rocks yield to the blows of the maul or can be broken up by explosives, the well must be abandoned.

Clay and sand often cling to the screen and render it worthless. To obviate this the pipe may be driven to the required depth with

[a] Veatch, A. C., Geology and underground water resources of a portion of northern Louisiana and southern Arkansas: Prof. Paper U. S. Geol. Survey No. 46, 1906, p. 97.

only a drive point and then pulled up a distance equal to the length of the screen. The drive point, which fits loosely on the pipe, remains behind and the screen is lowered upon it. This style of screen can also be removed and cleaned if it becomes clogged and ineffective, but it can be successfully used only when the depth to the water-bearing layer is known, since a test for water can not be made until the pipe is raised.

A modification of this outfit consists of a screen attached to a drive point and so arranged that the drive pipe slips down over the screen and rests on the point while the two are being driven. In testing for water the pipe is withdrawn a foot or two, a pitcher pump is screwed to its upper end, and the well is tested by pumping. If water is not procured at the depth tested the pump is removed and the pipe is driven down again to the drive point and deeper into the ground. The only drawback to this method is that pebbles may lodge against the screen when the pipe is withdrawn, and when it is driven down again they may tear the screen and impair its usefulness.

If the water that is tapped contains a large amount of iron a thick crust may form on the pipe and screen and reduce the inflow of water, or even shut it off entirely. The incrustation may be loosened and broken up into fine particles that may be pumped out with the water by pulling the pipe a few inches, by driving it down a short distance, or even by rapping the pipe sharply.

The driven well is used to a large extent in the Atlantic and Gulf coastal plains, and is becoming common in the Mississippi Valley and the prairie plains. It is much used to obtain water supply for stock in farm pastures where the ground water is a short distance below the surface. It has also been used with great success in army camps in many parts of the world. British army officials call it the Abyssinian well, as it was first used extensively for army water supply during the Abyssinian campaign of 1895.

The driven well has the disadvantage of using surface seepage water which is likely to be contaminated. The site of the well should therefore be carefully selected and the safety of the water be determined from the character of the material penetrated, the direction of surface drainage, and the depth of the well.

SPECIAL OPERATIONS IN DRILLING WELLS.

The sinking and finishing of wells involves a number of special operations and is attended by many difficulties. The following discussion pertains especially to wells put down with standard outfits (see pp. 34–55), although most of it is also applicable to wells drilled by other methods.

PACKING.

Necessity.—In constructing a well to obtain flowing water it is essential under some conditions that a water-tight joint be made between the casing and the rock; otherwise water that enters the well below the joint will find an outlet, and on rising outside the casing will enter porous sands at a higher elevation and fail to reach the surface. Furthermore, if porous rock is penetrated below the point to which the well is cased, it may be necessary in order to conduct the flow to the top to insert a line of tubing to a point below all such material.

In oil wells a small amount of water may enter at the point where the casing joins the rock without doing serious damage if the head of the oil is strong and forces all invading water to the surface, for the water may be easily separated from the oil in the receiving tank by gravity. A gas well, on the other hand, should be dry, unless the gas pressure is so great that all water is held back by it. Moreover, gas always escapes under natural pressure, while oil is not uncommonly pumped, so that in oil wells the water is brought to the surface and does not accumulate as it would in gas wells.

It was thought essential at one time that water should be cased off during drilling operations, but the presence of water in some of the Pennsylvania oil fields, notably at Macksburg, led the drillers to experiment successfully with "wet" hole drilling, which saves the cost of the additional casing otherwise necessary. Casing is not now so extensively used until the well approaches the oil sands.

Near Chicago a bed of soft shale occurs at a depth of about 1,000 feet. This material is prevented from caving and clogging a well by placing a packer below it and allowing a piece of pipe to extend upward from the top of the packer to a point above the upper surface of the shale. Where water under pressure is encountered in the shale it is necessary to extend the pipe until it reaches beyond the height to which the water will rise. Drilling is then continued through the pipe and packer.

In the Kittanning fields in Pennsylvania several gas sands are encountered. The pressure in the upper sands has been reduced by years of flow from the wells until it is much less than in the lower gas-bearing layers. If the gas is allowed to come into the well under its own pressure, it forces its way upward until it reaches the upper sands into which it leaks. This process sometimes results in one well supplying gas to an adjacent one. The discovery of the rejuvenation of gas wells in upper gas-bearing sands by sinking new wells to lower sands in which gas was under greater pressure led to recognition of the necessity for separating the several productive layers. For this purpose a gas packer, similar to the one shown in figure 9[13]

(p. 53), is lowered into the well to a point above the lower and more productive gas sands, with casing extending from the packer to the surface. This arrangement separates the gas of the upper and lower beds so that both sources can be drawn upon. In this way the entire flow of gas from the deeper sands is confined to the well that taps them.

Packing methods.—In oil wells the water in the rock between the surface and the capping stratum overlying the oil sands is shut out by first drilling 10 or 12 feet into the compact shale that ordinarily forms the overlying stratum. After the hole has been cleaned out a few bucketfuls of moist drillings are thrown into it and the string of casing is then inserted and set in these drillings in the bottom of the hole. The driller then redrills the loose drillings with a smaller bit. That portion of the cuttings which is between the casing and the wall of the well settles down very compactly and becomes as effective as clay in preventing water of higher water-bearing strata from entering the drill hole. The effectiveness of this operation is increased by a process called "reaming out the hole," which in this connection signifies the substitution of a smaller bit than the one previously used and drilling with a shorter stroke. In this way the wall of the well is made smoother than it would otherwise be, and the hole is tapered to a size a little less than that of the drive pipe. Into this funnel-shaped hole the pipe is gently driven, making a snug joint.

Testing joints.—The joint may be tested in two ways. In one method the casing is filled with water and allowed to stand. If the water does not sink away the joint is known to be tight. The other method consists of lowering into the well below the joint a casing tester—a funnel-shaped instrument with an anchor attached that enables it to be set at any point in the well. It fits the well snugly and prevents water from passing it on the outside. After it has remained in the well for a few hours or days it is withdrawn and examined. If it contains no water it is evident that no leakage occurs, and drilling will then be continued.

If a joint continues to leak after the casing has been reset, the pipe may be withdrawn, closed at one end, connected with the boiler, and tested by steam. If no defects are found it is put back and set into the rock at a greater depth. If the rock at the bottom of the casing is broken and full of crevices, a tight joint can not be made at that point. This condition occurs infrequently, but when it does happen, if it is imperative that the joint be made water-tight, an enlarging drill or reamer (fig. 6[6], p. 40) is used to make the hole large enough to let the pipe down to a point where a tight joint can be made in the solid rock. This obviates redrawing the entire string of pipe.

Flaxseed.—In the early days of oil exploration in this country a bag of flaxseed was sometimes inserted at the point where the casing

was to be set, the casing was let down, and that part of the bag which occupied the center hole was drilled out, leaving a considerable amount of seed between the casing and the well wall. This seed quickly swelled and closed the place in which it lay, thus preventing the entrance of water. Bags of beans and peas have also been used in a similar manner. For use a short distance above the end of the pipe the bag of flaxseed may be fastened around the casing, so as to swell and fill the space between the casing and wall of the well.

Cement.—Another method consists in filling up 5 or 6 feet of the bottom of the hole with cement, into which the casing is set. The cement hardens and excludes the water, and the portion within the casing is then drilled out. This method has been much used in the Baku oil fields of Russia, but its proper application is said to require great skill, as the settling qualities of cement are destroyed or seriously impaired by contact with oil or by the presence of large quantities of salt or other minerals in the water. Furthermore, the cement is expensive, and it deteriorates very rapidly if stored. Another unavoidable difficulty in its use inheres in the fact that there is usually water in the drill hole at the time that means are taken for its exclusion, thus making it necessary to convey the cement to the well bottom in tubes, and not allow it to filter through a long column of water. Flush-jointed, high-pressure tubes with extra long screw sockets are required for this work.

The process of cementing is carried on in Russia in a way very different from that followed in this country. The casing used is of unusually large size, ranging up to 36 inches in diameter. After being set it is entirely filled on the inside with a mixture of clay and sand, and cement is then carefully poured into the space between the casing and the rock. The cement excludes all water from this space and prevents its entrance into the well through imperfect joints or rivet holes, for the casing of Russian wells is not like that used in this country, but is thin, and the joints are riveted instead of being screwed together. After cementing has been completed the clay and sand on the inside of the casing are removed in the same manner as the original rock which occupied that space, but of course in a much shorter time, as the material has not had time to become compact.

Asphalt.—Asphalt has also been used for packing, being melted and poured down the outside of the casing so that when cool it forms a solid mass that water can not penetrate. The method is expensive, as the water in the well has to be heated with steam before the asphalt is poured in; otherwise the meeting of the two fluids congeals the asphalt and prevents it from flowing down where wanted. Trouble has also resulted from the refusal of the asphalt to set, even after considerable time, for, being viscous, it exerts a great external pressure on the casing and threatens to crush the latter if much is used.

This method of shutting out water has therefore not attained importance.

Rubber.—In many wells it is much more economical and effective to case off the water by rubber packers, which are made in styles to suit various conditions. The device in most common use (see fig. 9[13]) consists essentially of two metal cylinders united by a third hollow cylinder of rubber, usually an inch or two thick and varying in length and diameter with the special conditions to be met. This packer is lowered into the well by lengths of pipe to the position which it is to occupy. A weight is then dropped into it, which releases the wedges and spring, A (see fig. 9[13]); the spring throws the wedges up the taper of the cone, B, and when the packer is lowered under the weight of the drilling tools or casing the wedges catch the wall of the well. The rubber cylinder, C, expands outward and snugly fits all the irregularities of the well wall, thus preventing the passage of water. When once placed, this packer can be raised, but it can not be lowered again without being brought to the surface and reset.

In some wells where a small amount of oil or gas is struck in upper strata the attempt to obtain a greater production by drilling the hole deeper results in finding water instead of oil or gas. To shut off the water a packer consisting of a rubber plug with a tapering hole is used. A tapering mandrel, either of wood or iron, is driven into the plug and expands the rubber to fit the wall of the well so as to effectually shut off the water below.

Rubber packers are also employed in drilling wells where gas is encountered above oil-bearing strata. Instead of casing off the gas or allowing it to waste in the air a gas packer is introduced, which confines the gas between the casings and forces it to the surface.

After a packer has remained in a well for some time and has becomes embedded by the accumulation of sediment from the well wall it may be jarred loose and then removed by connecting it to a packer jar.

Concerning the durability of rubber packers it is difficult to make definite statements. It is, however, safe to say that the rubbers do not become useless from decay in a few years. The material used for packers contains probably not more than 60 per cent of pure gum. The greatest difficulty found in a packer made of high-grade rubber, and to a greater or less extent in any packer containing rubber, is its tendency to swell. This swelling does not affect the efficiency, but makes it very difficult to remove the packer if the casing is pulled for repairs or for cleaning. Packers are usually destroyed, not by rotting or by any chemical action while in the well, but by being torn during removal.

CLEANING.

In water-bearing or oil-bearing sand or rock that is firm and hard and will stand up in the well wall, a well may be completed simply by cleaning out the pores of the productive layers by strong pumping, which draws into the well the finer drillings that may have collected on the side of the hole and increases the delivery of water or oil. While cleaning is being done the pumps should not be stopped until sand is no longer discharged with the liquid, otherwise the sand will settle about the valves of the pump and make it impossible to start pumping again without drawing the pump rods and valves, cleaning them out, and resetting them.

An interesting operation in the care of oil and gas wells is the cleaning of the hole after the well has been producing for some time. Many of the first wells drilled in an oil or gas region penetrated only the first few feet of productive sand, the pressure being so strong at that depth that it lifted the tools from the well, or at least prevented further drilling. In time, however, such wells become clogged with sediment, the pressure decreases owing to the removal of gas and oil, and the wells must be cleaned to become profitable producers.

Where the sands carry gas or oil under light pressure, the hole is drilled through them and three or four feet into the underlying formation. A chamber is thus formed in which sediment may collect, leaving the whole surface of the sands available for the discharge of gas or oil. Some wells accumulate three or four feet of sediment in as many years. This settles and becomes as hard as the original rock.

In order to clean a well a derrick may be erected over it, as when it was first drilled. The other parts of the outfit used in drilling are then set up, the accumulated sediment is drilled loose and bucketed out, and the hole is deepened so that the advantage of the increasing pressure with depth may be obtained, or a reservoir supplied in which the collecting sediments may be caught. The derrick that one sees erected over oil wells in some oil districts is not usually the derrick used in drilling the well, but the one erected afterwards to clean the well or draw the pump rods, though in many districts the derrick used in drilling is retained. In cleaning out old wells whose rig timbers and wheels have rotted, resort is sometimes had to a mounted rig, which can be quickly run into position under the derrick.

At each cleaning a charge of 80 to 100 pounds of nitroglycerin is exploded in the bottom of the well to increase the yield. In many oil fields this is done regularly. Cleaning may become necessary again because of the caving in of the oil sand as the result of torpedoing, for in torpedoing the well even very hard rock is broken up and may cave into the hole. The cleaning of a well in this way often results in increasing the flow by 10 to 15 barrels a day. The operation

as above described costs about $400. Some wells are cleaned every three or four years; other wells drilled twenty years ago have not been cleaned since they were put down.

The pores of an oil well may also be cleaned by a process called "flooding." This is to be distinguished from the term "flooding" as applied to the natural entrance of water into the oil and gas sands. In order to clean a well by this process, a large quantity of crude oil is poured into the well down one side of the casing. This runs down with great velocity, and as it passes over the well wall it cleans out the pores by friction and suction, and thus allows a greater production. The yield of wells treated in this way is never greatly increased, but the operation is very simple and inexpensive, and the increase is generally sufficient to make it profitable.

SCREENING.

If the well is sunk into unconsolidated materials, such as glacial material, coastal-plain deposits, river flood plains, and waste-filled valleys, a screen must be used which will permit water or oil but not sand in serious amount to enter.

In the northern part of the United States oil wells are not usually obtained in unconsolidated materials, but in California and in Texas they are not uncommonly sunk entirely in such deposits. In the Texas oil fields the screens or strainers are made of ordinary pipe, usually 2 to 6 inches in diameter, perforated with holes about one-quarter inch in diameter and 2 inches apart. The pipe is then wrapped around with iron wire. If the sand is fine, the wire is wrapped close; if it is coarse, space is left between successive wrappings. This kind of strainer is supplied by machine shops throughout the oil fields, and can be made by any mechanic.

A water-well screen similar to the one just described is in use in the Mississippi Valley from St. Louis to the Gulf, and is made by wrapping No. 14 wire, 10 to 14 wires to the inch, around perforated wood or iron piping. The closeness of the wrappings, as in the case of the oil-well screens, depends on the fineness of the material to be screened out. Wooden piping or tubing as a base for the screen is often preferred for water wells on account of the rusting of iron pipe. In some wells these screens are 100 feet long. The weight of the wire screen and the impact of the sand pressing against it when set prevent the buoyancy of the wood from lifting the pipe.

Patented strainers are also used, especially in water wells. Some makes, like the Layne strainer, shown in figure 19, *a*, differ from the shop-made ones in the shape of the wire used. In the Layne and similar streainers the wire presents a smooth surface to the sand, and thus reduces the clogging of the screen and insures greater production and a longer life to the well.

The Cook well screen (fig. 19, *b*) is also in favor with water-well drillers and is used extensively throughout the United States. It consists of a single piece of seamless brass tubing, perforated by horizontal slits, which are made in different widths for different sizes of material, and are cut with a beveled edge on the inside of the screen

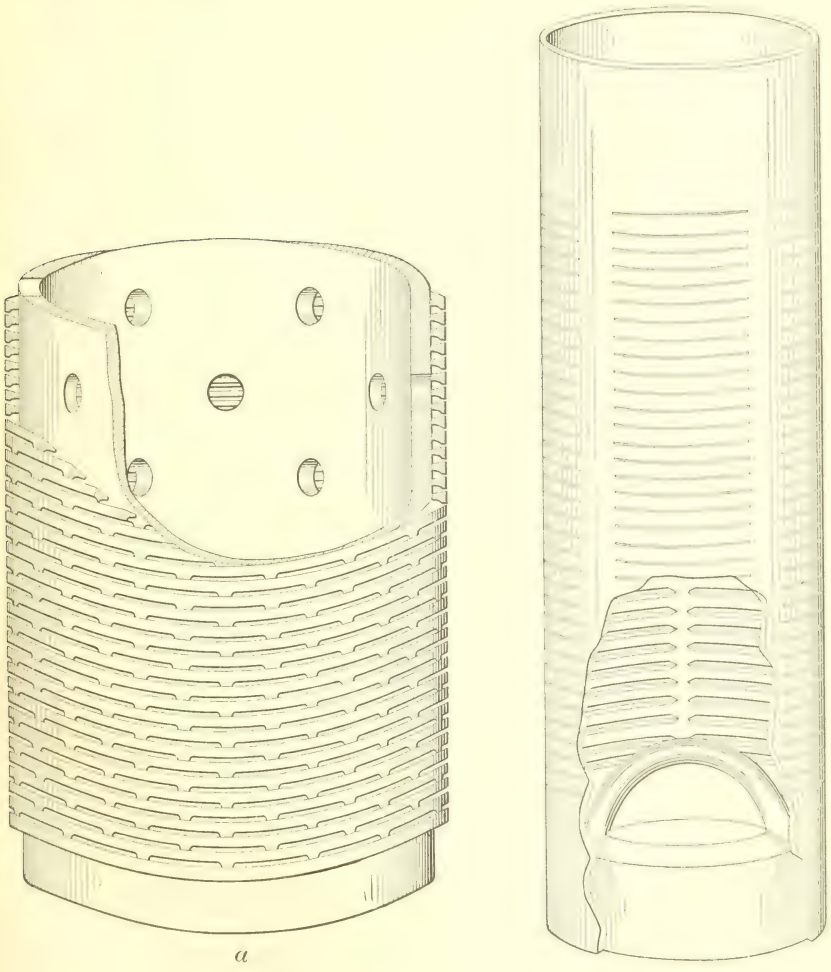


FIGURE 19. Well strainers: *a*, Layne strainer; *b*, Cook strainer.

to give a minimum amount of friction in the slit with a maximum amount of water delivered, and a smooth outer surface that reduces the clogging of the apertures to a minimum. The screen may be set in the bottom of the well, the pipe drawn until it is almost flush with the top of the screen, and a lead seal inserted at the joint, or the screen and pipe may be united by a screw coupling.

TORPEDOING.

OIL WELLS.

In an early record of the development of the Pennsylvania oil fields the following statements occur concerning the practice of torpedoing wells:[a]

In 1862 Col. E. A. L. Roberts, then an officer in the volunteer service and with his regiment in the Army of the Potomac in front of Fredericksburg, conceived the idea of exploding torpedoes in oil wells for the purpose of increasing the production. He made drawings of his invention, and in November, 1864, made application for letters patent. In the fall of the same year he constructed six torpedoes, and on the 2d of January, 1865, he visited Titusville to make his first experiment. Colonel Roberts's theory was received with general disfavor, and no one desired to test its practicability at the risk, it was supposed, of damaging a well. On the 21st of January, however, Colonel Roberts persuaded Captain Mills to permit him to operate on the Ladies' Well, on Watson Flats, near Titusville. Two torpedoes were exploded in this well, when it commenced to flow oil and paraffin. Great excitement, of course, followed this experiment and brought the torpedo into general notice. The result was published in the papers of the oil region and five or six applications for patenting the same invention were immediately filed at Washington. Several suits for interference were commenced, which lasted over two years, and decisions in all cases were rendered declaring Colonel Roberts the original inventor.

Nothwithstanding the success of the first experiment, operators were still very skeptical as to the practical advantages of torpedoes, and it was not until the fall of 1865 that they would permit the inventor to operate in their wells to any extent, from fear that the explosion would fill them with rock and destroy their productiveness.

Despite the above assertions several other men had, as early as 1860, successfully exploded charges of powder in oil wells in the attempt to increase their production.

Methods.—Many oil wells are now torpedoed as soon as possible after the oil sand is reached. For this purpose nitroglycerin in amounts ranging from 3 to 8 quarts is lowered into the well in tin shells provided with suitable firing heads. The shells are 3 to 5 inches in diameter and the length depends on the size of the charge used. The shell is placed in the top of the casing, fastened there, and filled by pouring in the nitroglycerin from cans. A lowering line is then attached and the charge is slowly lowered to the bottom of the well, when the hook at the top of the can disengages and the line is hauled up. For a large shot several shells are used, one resting on top of the other. If it is desired to shoot the well some distance from the bottom, an anchor is used. This is simply a small tube, which supports the shell at the proper depth. The nitroglycerin is then exploded by dropping into the well a small iron casing called a "go-devil," which strikes the can and explodes the charge. Another method of exploding is by means of the time fuse. The squib which

[a] Henry, J. T., The early and late history of petroleum, 1873, pp. 251–252.

carries the time fuse is made hollow in the center to hold about a pint of nitroglycerin, and into this nitroglycerin the end of a long fuse is inserted, on which is a large fulminate cap. The fuse is cut so as to burn a few minutes, according to the depth of the well. It is inclosed in a hollow covering, the interstices are filled with sand, and after lighting it, it is lowered on top of the charge.

Torpedoing, of course, is practiced only in wells whose production is slight when they are first drilled or becomes so after they have yielded oil for some time. A well may be finished for the torpedo by an enlarging reamer, which gives a chambered hole, and results in the charge producing greater effect. It is especially adapted to soft rocks where the crevicing of the oil sands can not otherwise be readily accomplished at a sufficient distance from the charge.

Effects.—In most wells the explosion takes place at so great a depth that there is little immediate surface effect, only a slight jar of the ground and a dull report being perceptible. In a few seconds, however, the enormous force of the explosion is shown by the violent ejection of oil, stones, water, and fragments of the tin shells.

The effects of shooting are not permanent, and after being shot many wells decrease permanently in yield. In some wells the flow may be again increased by lowering the tools and stirring the bottom—"agitating the well," as it is called. It is believed that when the tools are withdrawn a partial vacuum is suddenly created and the pores of the oil sand are cleaned by the heavier inflow of oil into the cavity formed by the explosion of nitroglycerin.

A good flow does not always follow a shot. Sometimes the shattered fragments, instead of being thrown out, become wedged together and choke up the hole. In this event the drilling tools must be put in again and the material drilled out. This is a disagreeable job, as the well is full of foul oil and the poisonous burnt products of nitroglycerin, which are occasionally thrown out over the men and the machinery.

When torpedoes are exploded in sands that are very friable large quantities of material fall into the hole and must be cleaned out. This is true of wells at Bartlesville, Okla., Casey, Ill., and Chanute, Kans. Agitation is also necessary in the friable sands, as so much material is finely pulverized by the explosion and driven into the pores of the sand that they are practically closed and oil does not begin to flow until they are opened again. That this action takes place is known from the stronger flow before than immediately after shooting and the flow after agitation of a very liquid mud, which is followed by a rapid increase in the flow of oil. The good effects of an explosion would therefore not be realized in friable materials if agitation were not practiced.

The explosion of a torpedo has a damaging effect on the casing if this extends down near the point where the discharge takes place, for it is bent and torn irregularly and is thus rendered more difficult to pull, should it be desired to save it later.

WATER WELLS.

Explosives are used to some extent in water wells for the purpose of increasing the supply and providing a reservoir for the water, and there appears to be no reason why, under favorable conditions, their use should not be as beneficial as in oil wells. If water is drawn from rock fissuring the rock will certainly increase the area from which delivery is made to the pump. In a limestone region, where the underground water, like the surface water, runs in more or less definite channels instead of percolating slowly as a broad and thick sheet, the torpedoing of a well would almost surely increase the number of contributory veins. In such a region the success of a well depends so largely on chance, the diameter of the hole being small and the water veins few, that torpedoing would seem to be beneficial to all wells and to determine absolutely the success of some. The experiment should be more generally tried.

FEATURES OF WELL CONSTRUCTION.

DIFFICULTIES ENCOUNTERED IN SINKING WELLS.

Accidents in well drilling are common and some of them may be unavoidable. Excessive strain on any part of the apparatus may cause it to break, and before drilling can proceed the broken parts must be removed and replaced. Many accidents are of trifling importance and cause little trouble or delay; others are very serious and may cause delays of weeks or months.

All the accidents that may happen can not be described here; only the more important ones will be noted. The common accidents may be divided into two classes—(1) those caused by losing tools in the well and (2) those due to geologic conditions. The contractor usually holds the driller responsible for accidents of the first class, but not for those of the second class, unless the formation is well known from previous borings.

LOSS OF TOOLS.

CAUSES.

Tools are usually lost as the result of one or more of the following conditions or causes:

1. A worn cable. The stretching and bending of the part of the cable immediately above the socket cause it to become thin and frayed after a few weeks' wear.

2. The imperfect attachment of the cable to the socket. The joint should be tested by putting a strain on the rope while the drilling tools are anchored at the surface.

3. Neglect in setting up the tools after each run. If the parts are not securely fastened together they become unscrewed and fall into the drill hole.

4. Paying out too much or too little cable. If too much cable is paid out, the jars will batter and break; if too little, the whole weight of the tools will fall on the cable and strain it excessively.

5. Crystallization of the iron of the tools through successive jarrings, brought about by the magnetization of the iron. The effect of magnetization on the drilling tools is to decrease their tensile strength. The screw pin of the auger stem may break from this cause.

Probably no other engineering operation requires more deftness and ingenuity than "fishing" in a drill hole, owing to the great depth of many drill holes and the small space in which the driller must work. To ascertain the nature of an accident one-half mile below the surface, in a hole perhaps only 6 inches in diameter, by means of a cable having a very appreciable stretch, is clearly an operation requiring great skill. As the string of tools is usually more than 50 feet long, weighs over a ton, nearly fills the hole, and is wedged in so tight that the strongest cable could not pull it loose in a straight pull, the conditions involved in some fishing jobs is obviously unusual. Occasionally the driller is compelled to break up the broken tool in the well, crushing it with the drill by repeated blows.

LOCATING LOST TOOLS.

The first step in recovering a lost tool is to learn the shape of its upper end and the position in which it lies in the well. This knowledge may be obtained by lowering over the tool a sheet-iron vessel containing soap or other soft material, in which an impression is easily made. An examination of the mold then enables one to determine the position of the tool and to devise means for its recovery.

If the fallen object has been caught in the well wall above the oil or water or lies in a dry hole, its position may be determined by reflecting light into the well from a mirror. It was perhaps this operation which suggested the invention of a photographic device for determinations of this character. The device has not been used much in this country, although it seems that where a considerable amount of money depends on the early completion of a well whose drilling has been delayed by loss of tools it could be used to great advantage. The device was invented by Mr. Loran, a Baku engineer, and both the instrument and process of photographing have been described by A. Beeby Thompson.

The device consists of a stereoscopic photographic apparatus, which is lowered to a point near the lost tool, light for the negative being furnished by an electric current carried by wires arranged in the camera. Concerning its construction Mr. Thompson says:[a]

An internally blackened, bell-mouthed vessel, at the small upper end of which is fixed the stereoscopic camera, and at the sides of which are fixed two small electric lamps with shades reflecting the light downward, is attached to a sinker rod with guides. Incased in an air-tight chamber above the photographic device is an electric accumulator, which supplies the light, and interposed in the circuit is a small clock that can be regulated to produce contact at any desired time, switching on the light and opening the camera shutter at the same moment. Above this is placed a cylinder in which compressed air is stored, leading by minute tubes to the bell-mouthed photographic vessel beneath. By a clever device a quick upward or downward motion of a few inches causes a disk, nearly equal in size to the well, working freely on the central spindle, to rise or fall and transmit a motion to a lever which actuates an air valve leading from the air vessel. The pressure of air must exceed the pressure due to the submergence of the apparatus in the liquid, and on the air valve being opened the fluid is displaced in the bell-mouthed vessel and an undisturbed view of the lost article is secured. After an exposure of one or two hours the air is shut off by a repetition of the before-mentioned jerk and the apparatus raised.

Some very good photographs made in this way are given in Mr. Thompson's book, showing the exact shape and position of fallen cable, wrenches, and other tools.

It is strongly urged that drillers in this country try the invention where it is very desirable that the exact position of the tools be determined before fishing operations are begun.

RECOVERING LOST TOOLS.

Most of the instruments made for recovering lost tools are expensive, and so many of them have been devised that one contractor can not afford to own a complete set. Usually he purchases first the ones he is most likely to need and others as he may require them.

Slip socket.—If the drill is lost in the well, but is not jammed tight, it may be possible to lower a spudding spear (fig. 20[1]) into the well and prod the top of the drill loose from the wall. The drill may then be grasped and removed by a slip socket (fig. 20[2]), which consists of a pair of slips inserted in a tubelike instrument and suspended by a light string. The teeth of the slips are beveled upward, so that when the socket is lowered the slips readily move downward over the upper part of the lost tool. By quickly jerking the socket upward the string supporting the slips is broken, the teeth bite into the tool, and as the socket is raised the beveled groove in which the slips work narrows the space and causes the grip to become more firm. In this operation it is essential that jars be used to cause the teeth of the slips to bite as deep as possible into the drill, and also to jar the drill from the

[a] Thompson, A. Beeby, The oil fields of Russia, 1904, 2d ed., 1908, p. 164.

rock in which it is held. If it is impossible to lift the tool, the socket may be driven down again. The slips are thus raised and are automatically caught on the side of the socket. If a harder pull on the object is required the socket should be brought to the surface and reset. If the jars should be broken and the string of tools fall into the well the tools may be withdrawn by lowering a slip socket of special pattern over the sides of the broken jar.

The slip socket was invented in this country and has been adapted to many uses and is more employed than any other instrument for lost tools. If it is properly arranged before being lowered into the well, it will not fail to seize the lost object and it grips it with greater and greater force as stronger pull is applied to the drill rope, and if the driller is unable to bring enough force to bear on the cable to withdraw the tools, it may easily be released and raised.

If tools have fallen far, and have become firmly embedded in the rock at the bottom of the well the fishing jars must be very long and the longest possible stroke must be given to the walking beam. The tools may usually be loosened by repeated blows and then removed.

Horn sockets.—If the tools have fallen only a short distance they may be removed by a horn socket (fig. 20[3]), a tube with two slits, cut on opposite sides, which when jammed down over the fallen tools expands slightly and obtains a friction grip. It is cheap, easy to operate, and is almost as much used as the slip socket.

Electro-magnet.—Another device used in fishing is a powerful electro-magnet, by which a lost tool may be drawn out of a niche in the drill hole and recovered. The electro-magnet has been used successfully by Mr. Phillips, of the firm of Phillips & Worthington, New York City, in drilling a well in New Jersey, but the rigging up of the apparatus is expensive and difficult.

Rope spear.—If the cable has broken near its connection with the temper screw and has fallen into the well it may perhaps be withdrawn by catching it with a rope spear (fig. 20[4]), a rod armed with upward pointing barbs, which is lowered into the well by a rope. If the drill is wedged in so tight that the cable can not be withdrawn by the spear a rope knife (fig. 20[5]) is lowered, by which the cable is cut off as near as possible to the drill. The drill may then be withdrawn by a slip socket and the cable speared and removed.

Defective casing.—Two instruments that are frequently used in dealing with defective casing are illustrated in figure 20[6-7]. If the casing has been dropped to the bottom of the well from a considerable height, it may be bent, or even twisted like a corkscrew, so that it can be withdrawn only in short sections. To do this the casing cutter (fig. 20[6]) is inserted, the knives of which expand as the pipe on which it is screwed is rotated, and the casing is cut at any desired point. If the casing is only slightly bent it may be straightened by the

use of a pipe swedge (fig. 20[7]), dropped into it repeatedly in the manner in which the drill is operated from the walking beam.

REDRILLING AND ENLARGING.

If the methods just described are ineffective in removing the broken parts, the driller may shift the drilling tools a few inches to one side and redrill and enlarge the hole. By drilling some distance below

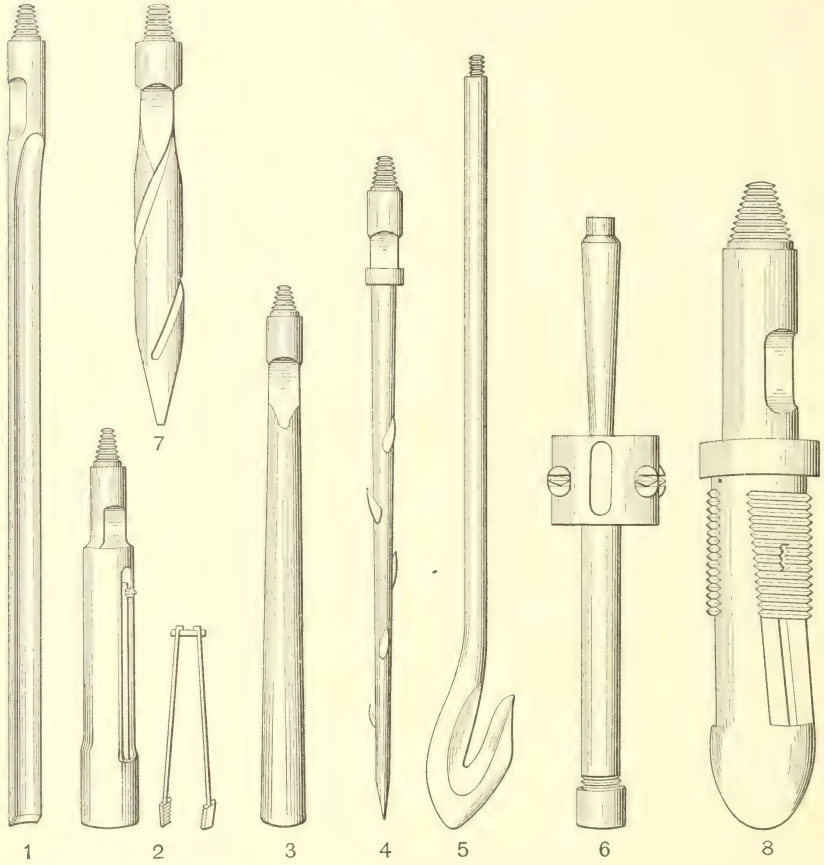


FIGURE 20.—Fishing tools used with standard drilling outfit. 1, Spudding spear; 2, slip socket for tools; 3, horn socket; 4, rope spear; 5, rope knife; 6, casing cutter; 7, pipe swedge; 8, slip socket for inside of pipe.

the level of the top of the lost tools and spearing them out into the new hole, part of them may usually be grasped by a slip socket and withdrawn. If the drilling is done in relatively soft material the tools may be pushed to one side and passed by, thus drilling a second hole. This at first seems to be an almost impossible operation, but it is easily done, and is effective in disposing of even large broken instruments.

GEOLOGIC DIFFICULTIES.

SPALLS.

Spalls of rock or loose stones may fall from the wall of the hole on top of the drill and wedge it in so tightly that it can not be withdrawn by cable pull alone. This is a common accident in wells in highly creviced or fissured rock or in glacial till, without casing or drive pipe. The spalls or loose stones may usually be broken up by a smaller drill, and the tools can then be withdrawn.

In brittle sandstone and in shale the top of the string of tools may become jammed in a cavity in the wall of the well, made by the detachment of rock fragments. It is then necessary to bring the string of tools into their normal position in the drill hole by means of the spudding spear. They can seldom be loosened simply by playing on the cable.

BOWLDERS.

An incident that shows the close dependence of drilling on geologic conditions is the mistaking of a bowlder for bed rock. Ordinarily the driller determines whether the hard rock which the drill has struck is or is not a bowlder by noticing whether it seems loose and rebounds under the stroke of the drill. If it does not seem to be solid rock he endeavors to break it to pieces and remove it.

The bowlder may be so large that the driller mistakes it for bed rock, and after drilling into it for 3 or 4 feet sets the casing in the bowlder, substitutes a smaller drill, and proceeds as if he were in bed rock, but after drilling a few feet farther he again encounters sand or clay of the same character as that above the bowlder. He must then draw the casing set in the bowlder and ream out the hole to a size which will enable him to sink the proper casing through it.

The error of mistaking a bowlder for bed rock may be avoided by observing the drillings brought up to the surface and noting whether they are of material like the bed rock in the vicinity. In northern Indiana, for example, a driller may be pretty certain that if the drillings indicate granite, or schist, or trap, the drill is in a bowlder and not in the bed rock, which in that region is for the most part limestone. If the rock appears to be a bowlder, he will of course expect to find soft material below it and will proceed accordingly.

In the glaciated regions of North America the bed rock is overlain by a bed of till that ranges in thickness from a few feet to several hundred feet and contains many large bowlders. The bed rock in most places is shale, sandstone, or limestone, but the bowlders, having chiefly come from the north where the rocks are of different character, are chiefly of granite, schist, and other crystalline rocks; some bowlders, however, as those derived from the country rock, are of limestone and sandstone.

If a bowlder is especially hard, it may be blown to pieces by dynamite or rock powder tamped with a bushel or two of dry sand or clay. This may split the bowlder so that the casing will pass down between the broken parts, or it may break it into pieces so small that they can be further reduced by the drill and removed by the bailer. If the bowlder is to be broken by explosion, the casing should be drawn 3 or 4 feet above the charge, so that it will not be injured.

RUNNING MUDS AND CLAYS.

Mud produced from some shales hardens quickly when exposed to the air. If such mud runs into a well and fills the space between the drill and the well wall, it may solidify and interfere with the withdrawal of the drilling tools. A hole drilled through a stratum of such shale must be cased down and drilling must be pushed forward so rapidly that the mud will not have time to solidify. The drill may be freed from obstruction by this mud and withdrawn by slowly working it up and down so as to gain on the upstrokes, and the mud may be removed by small buckets or augers. If this method fails, 1½ or 2 inch pipes may be lowered into the well and the hardened mud and sand may be flushed out by a powerful water jet. Such a layer of mud and clay can sometimes be passed by casing it off with a short length of pipe and using a smaller drill, but the driller usually prefers to work patiently past it rather than to reduce the size of the hole by casing it off.

Even if only a small quantity of water is present, clay will "crawl" and relieve pressure by squeezing through very small openings in threads or sheets. The slow but forcible movement of plastic clay into a drill hole may fill the hole during a single night when drilling is suspended. When drilling is resumed the next morning the drill will strike this soft plug of clay and ram it down until the compression of the air below prevents its further movement. The drill may continue to pound on this elastic cushion for days, or even weeks, without making further progress while the clay slowly accumulates in the hole. The difficulty may be overcome by casing off the clay before it forms a plug or by jetting through the plug. Plastic clays are encountered in South Dakota and in the Atlantic coastal plain, but most of the glacial clays are so sandy that they yield readily to the drill even if the well does become clogged.

QUICKSAND.

Character of the material.—In drilling water wells in the soft coastal-plain formations that stretch from Cape Cod westward and southward along the border of the continent the most serious difficulty encountered is caused by beds of quicksand, which are as a rule

interstratified with beds of coarser sand and of clay. The quicksand comes into the drill hole and must be bailed out in large quantities before the casing can be driven farther down and drilling continued. Under ordinary conditions quicksand will not yield its contained water, and therefore if it has a tendency to rise in the pipe the difficulty can seldom be obviated by pumping alone. The whole mass is saturated, its water can not be separately withdrawn, and it exerts practically hydrostatic pressure.

A driller in the Northern States may find pockets or lenses of clay or coarse sand in a quicksand layer, and these cause him to think he has passed through the quicksand. Coarse sand, such as "bar" sand, will not rise if the velocity of the water through it is less than about 2½ feet per minute. The drive pipe shuts off the water and quicksand above such a pocket of coarse sand or clay, but as soon as the drill penetrates the pocket the quicksand flows in and may rise to the height of the top of the deposit. If the bed is 20 feet or more thick, the pipe can not be driven through it on account of the resistance of the compact sand; and if the water in it is under great head, so as to force the sand up to or above the point at which the bed was struck, further progress may be almost impossible. In some wells quicksand has risen in the pipe 100 feet above the depth at which it was struck.

Pressure of material.—If the drill hole is not kept full of water, the pressure exerted by quicksand on well casing may be very great. Experiments have shown that quicksand saturated with water exerts a lateral pressure equal to one-half its vertical pressure. Beyond the point of saturation the pressure is hydrostatic, the vertical and horizontal pressures being equal. Quicksand can be confined only by using water-tight casing, for it is commonly so fine that it will pass a standard 100-mesh sieve. Saturated material of this fineness will flow wherever water flows. The lateral pressure of quicksand is exceeded only by that of clay, and the clay moves much more slowly.

Withdrawing tools.—When quicksand is encountered not only does the material require laborious excavation, but unless the drill is withdrawn rapidly it gets jammed in the hole and is buried by the sand. The driller is then under the necessity not only of cleaning out the hole, but also of recovering the drill before he can resume drilling. In this event it is usual to bail out the quicksand to the point at which the drill is stuck and then introduce into the well a wash pipe an inch or two in diameter. With this the quicksand is agitated (or jetted) and washed down to the surface. This operation continues until the drill is partly free, when a slip socket is inserted over its upper end and, with the assistance of the fishing jars, it is jerked free from the quicksand.

In connection with the up-and-down motion given to the drill while it is being removed from the quicksand, it must be raised with

each stroke, and in this way gradually freed. The same method of procedure is required where quicksand comes into a well suddenly, the drill being moved up and down as if it were cutting into rock, while at the same time it is lightly raised at each upstroke. This operation must be carried on rapidly, otherwise the sand will pack about the drill and prevent its removal.

If the driller is working in sand of rather fine texture, he draws the drill at night, as otherwise the sand may creep up around the drill and "set" almost as hard as rock. The drill is seldom left in the well overnight on account of the danger from sand or of malicious cutting of the rope, or, in a rock well, of having a bowlder fall and become jammed between the drill and the well wall.

Penetration of quicksand.—If the layer of quicksand is only a few feet thick it may be penetrated by bailing out and then driving the casing. The pipe is driven as far as possible into the bed without bailing, and the quicksand may occasionally be passed through at one drive.

A thin bed of quicksand that lies near the surface may be shut off by driving sheet piling around the mouth of the well.

Difficulty caused by quicksand may be partly overcome by filling the bottom of the well with mortar or Portland cement, which sinks down through the quicksand and sets. The hole may then be drilled through the cement, which forms a wall that prevents the further inflow of quicksand. Stones, clay, and asphalt have also been dropped or poured into the hole to restrain the quicksand, with some success.

Water pressure.—The head of the water in quicksand is nearly always less than the elevation of the well mouth. Some drillers maintain that quicksand can always be penetrated by keeping the drill hole full of water. If the quicksand lies at a depth of several hundred feet and its head is 100 or 150 feet below the surface, a column of water in the well will exert a back pressure on the quicksand of 43.4 pounds per square inch for every 100 feet of drill hole, which will prevent it from rising in the pipe. The sand bailer may then be inserted and the well may be bailed through the column of water.

It sometimes happens that after bailing out large quantities of quicksand the pipe becomes bent, a fact that is explained by assuming that the quicksand bailed out is removed from beneath a higher layer of firmer material, such as till or clay, on only one side of the pipe, and that the pressure of this material against one side of the lower end of the pipe causes it to be thrown out of alignment. The remedy consists in keeping the hole full of water. This prevents the formation of such an artificial cave; or if the pipe has already become crooked, corrects the trouble by causing the pressure on the pipe to be equal on all sides.

If such a cave is formed beneath a layer of till, bowlders may fall down from its walls and become jammed against the pipe and prevent it from being driven ahead. The side pressure caused in this way may likewise be at least partly overcome by keeping the hole full of water. If the trouble is not remedied by this means, the process may be supplemented by drawing the pipe until the drive shoe is above the bowlder. The bowlder may then be crushed with the drill and the pipe driven ahead.

Pumping.—By keeping the shaft full of water, J. E. Bacon, in sinking a large open well at Charlotte, Mich., in 1904, removed quicksand by a powerful sand centrifugal pump. This method was also successfully employed at Millville, N. J., in sinking a well 8 feet in diameter to a depth of 36 feet, the lower 16 feet being through fine, saturated sand.[a]

Freezing.—Quicksand has been penetrated by shafts by means of freezing. This method was first employed in 1883 by F. H. Poetsch, a German mining engineer, who by using it sunk a shaft in a mine near Schneidlingen, Prussia, through a bed of quicksand about 18 feet thick, lying about 100 feet below the surface. As other methods had proved unsuccessful, Poetsch drove pipes into the quicksand and circulated through them a refrigerating brine which froze a wall of quicksand 5 feet thick around the proposed shaft. Excavation was continued within this wall, and the shaft was carried downward through and below the quicksand. The same engineer later excavated through 107 feet of quicksand by the same means. The process has also been used in this country in sinking a number of shafts, one of which is described by D. E. Moran.[b] The machinery used in freezing the quicksand consisted of the following essential parts:

1. An ammonia compressor or pump with suitable motive power.

2. Pipe coils surrounded by constantly changing cooling water. In these coils the compressed and heated gas coming from the ammonia compressor is cooled to such a temperature that, at the pressure existing in the coils, it condenses to the liquid form.

3. A valve, regulating the flow of the liquid ammonia from the above-described coils into—

4. A second set of pipe coils, surrounded by brine or other vehicle. The liquefied ammonia passes from the regulating valve into these coils and immediately expands, absorbing the necessary heat from the surrounding brine. From the coils the gas is led back to the compressor, completing the cycle.

The brine used was a 60 per cent solution of the impure calcium chloride of commerce. The cold brine was pumped from the refrig-

[a] Ledoux, J. W., Eng. News, Mar. 12, 1903, p. 237.

[b] Moran, D. E., The freezing process as applied at Iron Mountain, Mich., in sinking a shaft through quicksand: School of Mines Quart., vol. 2, 1890, pp. 237–254.

erating tank through a system of distributing pipes and regulating valves to the ground pipes, and after circulating through these it returned to the refrigerating tank, the velocity of the brine in the downward flow pipes being about 2 feet a second. No protection was given to the connecting pipes above ground, so that these were soon covered over with a snow-like ice, the result of condensation from the atmosphere, and this served as a cheap and effective lagging.

Soon after the brine was started in circulation the ground began to freeze around each pipe, forming frozen cylinders, which increased in diameter until at the end of six days adjacent cylinders intersected and made a circular wall extending from the surface to the bottom of the drive pipe and thus formed a cofferdam inclosing the proposed shaft. Excavation was then begun inside this cofferdam, and no water came through the frozen wall at any time. The rate of freezing differed in different parts in the deposit, depending on the amount of water the parts contained. The smaller the amount of water the longer it required to effect freezing.

Some of the physical qualities of the frozen quicksand were noted.

Frozen quicksand may be regarded as a mortar in which the cementing material is ice, and, as in a cement mortar, the strength will probably be found to depend on the quality of the sand and the presence of sufficient cementing material, as well as on the strength of the cement.

Frozen quicksand looks like a fine-grained sandstone. It is perfectly homogeneous, breaks with a tendency to conchoidal fracture, and is as hard to work as a stone of similar character. When mixed with gravel or bowlders the mass resembles conglomerate or a concrete made with similar stone. The difficulty of working the material is more than doubled by the presence of gravel, which greatly increases its density and dulls the pick points or "moils" of the miners. The strength with which the quicksand adheres to the stone is shown by the line of fracture in such material. There seems to be no tendency for the rounded bowlders to pull out of the quicksand, but rather for the break to follow the shortest line, whether through flint or quicksand.[a]

Quicksand beds that lie near the surface can be thus frozen without very great expense, but the expense of freezing beds that lie at depths of over 100 feet will probably be great and the process will be slow.

FLOODING OF OIL WELLS.

DEFINITION.

Irremediable injury is constantly being wrought in both old and new oil fields by "flooding"—the invasion of the oil or gas bearing stratum by water from some higher source.[b] As water is heavier than either oil or gas, it displaces these substances or becomes mixed

[a] Op. cit., pp. 248–249.

[b] The term "flooding" is also used locally in another sense with reference to cleaning wells (see p. 98).

with them, and not only damages the well into which the water first enters, but also floods the contiguous sands and may result in the destruction of an oil district.

CAUSES.

Some oil men contend that the admission of water to beds of productive sands will affect the production of a well by raising the oil or gas above the level of the bottom of the casing, but the whole surface of the productive sands on the well wall is left exposed, and any rise of oil or gas in the sands themselves would not affect their relation to the well.

In some wells flooding produces a mixture or emulsion of oil and water, which in the rock can only very slowly separate again under the influence of gravity.

Oil usually rests on salt water, and in order to keep the well in good condition as long as possible the oil should be pumped off the water slowly. In a state of rest the oil and the water are separated by gravity. The flow of oil from a well producing 500 barrels a day is so slow that it does not disturb the water, but if the amount is as great as 5,000 barrels a day the oil is drawn over the water so rapidly that the two are to some extent churned into an emulsion, and this effect probably extends some distance into the porous beds containing the oil.

An emulsion is also formed if the well has been put down too far into the oil-bearing strata and the water level has risen by reason of continued and rapid outflow of oil. Forced production is often practiced, however, because it enables the owner of one well to draw oil from under his neighbor's property before his neighbor has had time to sink a well. In small fields this forced production is important, because the oil is soon exhausted, and each well owner tries to get as large a share of the supply as possible.

Rapid pumping may exhaust a well and cause water to rise in the area around its lower end so as to flood adjacent wells and render them useless, as was shown in the fields at Chanute, Kans., at Humble, Tex., and some fields in Illinois.

Rapid pumping may have the further disadvantage of making it necessary to store large quantities of oil at the surface, where 25 per cent of it may be lost during a single summer by evaporation. The sand or rock originally holding the oil is its best reservoir, because it does not permit evaporation, and it furnishes the maximum yield.

Well owners have apparently not realized the importance of considering the durability of well casing in connection with flooding, yet the decay of the casing is probably the chief cause of the trouble.

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A well to which water has had no access for a score or more of years may be suddenly rendered useless by flooding caused by decay or break in the casing. It is more probable that by action of minerals in the water, chiefly iron sulphate, the pipe has been corroded and water allowed to come into the well.

Another source of flooding may be an abandoned or "dry" well—one that does not yield oil or gas, but contains water. The hole may have been drilled into sands that yield oil at some near-by point, and unless the hole is properly plugged before it is abandoned water from it may enter the oil sand, find its way into neighboring wells, and cause great damage.

Where the rock throughout an oil field is widely flooded, as from abandoned wells whose locations even are no longer known, there seems to be no remedy for the flooding, either by pumping or by drilling deeper.

PERMANENT EFFECTS.

The permanence of the effects of flooding may be judged from the results of experiments made by a number of well owners. Mr. L. C. Sands, secretary of the Oil Well Supply Company, attempted over twenty years ago to restore a flooded area at Elizabeth, W. Va. The wells of the locality produced oil before the civil war at the rate of 200 to 300 barrels a day, but when the war began they were abandoned and water accumulated in them. Mr. Sands purchased about 1,000 acres of oil-producing land and attempted to pump the water off the oil sand. The pumping was continued for a long time, but the yield of oil was increased only about a barrel a day, and the experiment was therefore abandoned.

Flooding is a serious matter. Again and again it is caused by the ignorance or carelessness of the drillers that first enter a field, who practically destroy all chance that it will ever be successfully exploited. "Wild-cat drillers" in a new field, who work rapidly and move from one place to another, frequently cause flooding, for they drive many wells that do not yield oil or gas and abandon them without casing off the water or properly plugging the wells. Even the casing may be withdrawn. Later, oil may be found near by and after being pumped for some time begins to show water, which has entered from the hole first drilled and flooded the sands—that is, has partly displaced the gas and oil.

The term "wild-cat driller" is not used here in an odious sense, for the name is applied to one who drills in a locality where oil or gas has not been previously found—that is to say, to a driller engaged in exploration. The only odium attached to the name is caused by the inefficiency or carelessness displayed by some drillers in every locality.

STATE LAWS FOR PREVENTION.

To guard against flooding, several States in which oil and gas are found have passed laws making it an offense to abandon a drill hole without first plugging it with a wooden plug of a specified length, to be driven down by the drilling tools. The wood swells under the influence of the water and presses against the inner surface of the casing, firmly sealing it at the bottom. Most of the laws prescribe the distance above or below the oil sands at which the plug is to be driven.

If water fills the well to a considerable depth it is difficult to lower through it a plug of the required size, hence the plug is made in the form of a hollow cylinder, which is lowered to the well bottom, and a pin or plug is firmly driven into it by the string of tools. Several feet of earth are then thrown on top of the plug to complete the sealing process. If oil and gas are found at several horizons plugs must be inserted below the lowermost and above the uppermost horizon, and if a water-bearing stratum lies between oil and gas bearing strata this must be plugged satisfactorily both at its top and bottom. In addition the top of the well must be closed by a plug.

So far as the writer knows there is no officer whose duty it is to enforce this law, but prosecution is usually begun on the complaint of residents or well owners in the vicinity of a well that is abandoned or is to be abandoned. It is difficult to enforce the law because the evidence of the plugging can consist only of the word of the driller or contractor, and is impossible to discover by direct observation more than the approximate depth at which the plugs were placed or the manner in which they were inserted.

A few of the statutes relating to the plugging of abandoned wells are quoted here, as they show the seriousness with which flooding is viewed.

In Pennsylvania a law passed June 10, 1881 (sec. 1, P. L. 110), prescribes that—

> Whenever any well shall have been put down for the purpose of exploring for any producing oil, upon abandoning or ceasing to operate the same, the owner or operator shall, for the purpose of excluding all fresh water from the oil-bearing rock, and before drawing the casing, fill up the well with sand or rock sediment to the depth of at least 20 feet above the third sand or oil bearing rock, and drive a round, seasoned, wooden plug at least 2 feet in length, equal in diameter to the diameter of the well below the casing, to a point at least 5 feet below the bottom of the casing, and immediately after the drawing of the casing shall drive a round wooden plug into the well, at the point just below where the lower end of the casing shall have rested, which plug shall be at least 3 feet in length, tapering in form, and to be of the same diameter at the distance of 18 inches from the smaller end as the diameter of the well below the point at which it is to be driven [and] after it has been properly driven, shall fill in on top of same with sand or rock sediment, to the depth of at least 5 feet.

Ohio has statutes equally specific, as follows:

SEC. 306–4. It shall be the duty of the owner of any well drilled for gas or oil and which in drilling shall have passed through any vein of mineral coal, before abandoning, or ceasing to operate such well, and before drawing the casing therefrom to seal the same in the manner following: There shall be driven in such well to a depth of at least 10 feet below the floor of the lowest coal measure a round seasoned wooden plug at least 3 feet in length and equal in diameter to the well at that point, on the top of which plug shall be filled at least 7 feet of sediment or drillings, or cement and sand. Where any gas or oil well passes through any gas or oil bearing rock lying above the coal measures, the owner of said well or his agent shall, upon abandoning or ceasing to operate such well, drive a dry wooden plug not less than 2 feet in length, equal in diameter to the diameter of the hole, to a point as near as possible to the top of the coal vein, on the top of which plug there shall be filled at least 5 feet of sediment or drillings, or cement and sand, as the mine inspector shall direct.

In case such well is not plugged as aforesaid within ten days from the abandonment thereof, the chief inspector of mines or a district inspector of mines may cause the well to be plugged, and the costs and expenses of such plugging may be recovered of the person, firm, or corporation whose duty it is to plug the same, in the manner provided for the recovery of penalties by section 303–5 of the Revised Statutes of Ohio.

Indiana well owners are protected by the following statute:

SEC. 651. PLUGGING ABANDONED WELLS. 2. Whenever any well shall have been sunk for the purpose of obtaining natural gas or oil or exploring for the same, and shall have been abandoned or cease to be operated for utilizing the flow of gas or oil therefrom it shall be the duty of any person, firm, or corporation having the custody or control of such well at the time of such abandonment or cessation of use, and also of the owner or owners of the land wherein such well is situated to properly and securely stop and plug the same as follows: If such well has not been "shot" there shall be placed in the bottom of the hole thereof a plug of well-seasoned wood, the diameter of which shall be within one-half inch as great as the hole of such well, extend at least 3 feet above the salt-water level, where salt water has been struck; where no salt water has been struck such plug shall extend at least 3 feet from the bottom of the well. In both cases such wooden plugs shall be thoroughly rammed down and made tight by the use of drilling tools. After such ramming and tightening the hole of such well shall be filled on top of such plug with finely broken stone or sand, which shall be well rammed to a point at least 4 feet above the Trenton limestone, or any other gas or oil bearing rock; on top of this stone or sand there shall be placed another wooden plug at least 5 feet long with diameter as aforesaid, which shall be thoroughly rammed and tightened. In case such well shall have been "shot" the bottom of the hole thereof shall be filled with a proper and sufficient mixture of sand, stone, and dry cement, so as to form a concrete up to a point at least 8 feet above the top of the gas or oil bearing rock or rocks, and on top of this filling shall be placed a wooden plug at least 6 feet long, with diameter as aforesaid, which shall be properly rammed as aforesaid. The casing from the well shall then be pulled or withdrawn therefrom, and immediately thereafter a cast-iron ball 8 inches in diameter shall be dropped into the well and securely rammed into the shale by the driller or owner of the well, after which not less than 1 cubic yard of sand pumping or drilling taken from the well shall be put on top of said iron ball. (R. S., 1897, sec. 7888; R. S., 1901, sec. 7511.)

The following law also makes it possible for others besides the well owner to remedy the defect and recover the cost of the labor and material:

SEC. 653. LIABILITY. Whenever any person or corporation in possession or control of any well in which natural gas or oil has been found shall fail to comply with the provisions of this act, any person or corporation lawfully in possession of lands situated adjacent to or in the vicinity or neighborhood of such well may enter upon the lands upon which such well is situated and take possession of such well from which gas or oil is allowed to escape in violation of the provisions of section 1 of this act, and pack and tube such well and shut in and secure the flow of gas or oil, and maintain a civil action in any court of competent jurisdiction in this State against the owner, lessee, agent, or manager of said well, and each of them jointly and severally, to recover the cost and expense of such tubing and packing, together with attorney's fee and cost of suit. This shall be in addition to the penalties provided by section 3 of this act. (R. S., 1897, sec. 7890; R. S., 1901, sec. 7513.)

CONTAMINATION OF WATER WELLS.

USUAL METHODS OF PREVENTION.

In water wells less care is exercised in packing, plugging, and casing than in oil or gas wells, though the neglect may have serious sanitary results even if it is of less obvious economic importance.

The water in water wells may be contaminated and rendered unfit for use by allowing water from other sources than those yielding desirable supplies to enter the well. If the well is sunk to a water-bearing bed whose water is made unfit for use by a large content of dissolved minerals, the undesirable water may be shut off by plugging the well above the point where such water is encountered, so that only the shallower supplies will be drawn upon. For this purpose it is customary to use a wooden plug, which expands under the action of the water and fits the well tight. Earth is then thrown on the plug and compacted, and when the plug has decayed the earth itself prevents further trouble.

In drilling a well water may be found at several levels, one of which yields unpalatable water, and it is then desirable to separate the different water-bearing beds and determine the source of the undesirable water. By the proper arrangement of pipes, packers, and plugs, each water-bearing bed can be separated from the others and examined, and when the undesirable bed is located water from it can be excluded by casing it off.

EXAMPLES OF CONTAMINATION.

At a number of places in South Carolina water has been obtained by sinking deep wells, uncased below bed rock, into the fissured crys-

talline rocks that lie below the soil layer. Of these wells L. C. Glenn says[a]:

The deeply drilled hole has cut across enough such fissures to obtain a large supply of water for the pumps, yet this water is derived not from a great depth nor from a long distance, but from the great body of ground water near the surface and immediately around the well. If the fissures in the solid rock are very numerous, the area supplying the water is an inverted cone whose apex is the lowest point of entry in the bore hole and whose base is a large circular area of the ground-water surface around the well mouth, and only one, two, or three score feet beneath the surface of the town, with its innumerable sources of pollution of every kind. If the well is supplied by only one fissure or by a few fissures, they must be correspondingly large and furnish more direct and easy lines of flow to the well. They may extend almost uninterrupted nearly up to the surface and furnish a direct channel for surface waters to enter the well.

The amount of water that can be pumped from such wells is usually large and analyses made when the well is first completed have shown a good, pure, clear, and usually soft water, well adapted to almost any purpose. But while at first such deep wells may be protected from contamination by the surface-soil layer, which acts as a filter, and the water may be pure and wholesome, yet they are very apt sooner or later to become contaminated. Constant pumping from them soon causes the indrafts supplying the water to open better channels through the fissures and allows more direct ingress of waters from the surface. These channels sooner or later are able to carry surface contamination directly into the well. Such deep wells are therefore at best open to grave suspicion and constantly need careful watching. This need is all the more necessary because of the fancied security given by the very favorable analysis of the water when first used. Such careful watching will usually result in the condemnation and closing of the well in a few years, especially if the town be of considerable size, so that there is furnished to the soil a large amount of contaminating organic material. A well of this kind drilled over 2,000 feet deep in Atlanta, Ga., some years ago, which at first furnished a large amount of acceptable water, was ordered closed by the board of health after a few years' use because of sewage pollution.

Two specific illustrations of the contamination of water wells have been furnished by the late J. E. Bacon, hydrologic engineer, as a result of experiments made to improve the water supply of Saginaw, Mich., and Dallas, Tex.

Previous to 1902 a part of the city supply of Saginaw was drawn from a deep-well system consisting of about 20 bored 4-inch wells, having depths ranging from 89 to 230 feet. These wells, most of which penetrated bed rock, were being contaminated by the infiltration of brine from abandoned salt wells. Up to the time Mr. Bacon began his investigations almost no attempt had been made at Saginaw to protect ground water from contamination of this kind. The seriousness of the situation may be understood from the fact that possible sources of ground-water supply at Saginaw are limited to the loose sands and gravels that overlie the rock and to the upper layers of the rock itself. Manifestly the only way in which this water can

[a] Underground water of South Carolina: Water-Supply Paper U. S. Geol. Survey No. 114, 1905, pp. 143, 144.

be kept pure is by plugging abandoned salt wells at a suitable distance below the surface and by exercising great care in maintaining the casing of other wells intact. The contamination has been partly remedied and purer water is obtained for municipal purposes from the glacial sands and gravels that overlie the sandstone.

At Dallas, Tex., water is yielded by four geologic formations.[a] One of the city wells penetrates a formation (the third in downward sequence) whose water has a high temperature and is so strongly mineralized as to be extremely unpalatable and unfit for domestic supply, though it is somewhat used for medicinal purposes by a number of the residents of the city. This water is so corrosive that casing that had been in the well only one year showed many breaks and checks, several of them half an inch in diameter. The threads at the casing joints were so completely destroyed that when an attempt was made to pull the casing each length was lifted out as if it had no connection with the piece below. As a tight casing it was practically valueless. As the water in this formation is under greater head than that in the next water bearer above, the sands of the latter were becoming impregnated with the mineral substances contained in the lower water. By inserting a packer in this well between the two formations, with piping to the surface, the two waters were separated, the mineral water coming up inside the pipe and that from the higher formation rising between this pipe and the well casing. Differences in head and in the quality and temperature of the waters were at once noticed. Although the water from the higher beds was at first notably mineralized, the mineral content decreased with continued use.

RESULTS OF DEFECTIVE CASING.

Iron pipe put into the ground in the form of a sewer is not expected to last more than ten to fifteen years, but if it is put into the earth in the form of a well casing it is usually tacitly assumed that it will last indefinitely. That casing suffers deterioration and decay and that it should be examined at intervals for resulting defects is, however, shown conclusively by its condition when it is withdrawn after having been in the earth only a short time.

The life of a casing can not be definitely predicted, the rate of its decay depending on the special conditions in each well. Casing withdrawn from some wells fifteen to twenty years old has been found to be in fairly good condition except at the joints, though as a rule at this age it is too badly corroded to be withdrawn at all.

Decay of the casing may result in admitting to a well, and thus polluting the supply, undesirable water that was originally cased off. Recasing the well then becomes necessary.

[a] Hill, R. T., and Vaughan, T. W., Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Tex.: Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1897, pp. 199–321.

In artesian basins where many wells have been sunk the head may be greatly reduced and wells near the border of the basin may even be rendered nonflowing by allowing the wells to discharge continuously. To prevent this needless tax on the underground supply, a number of States have passed laws prohibiting the waste of water from flowing wells and requiring the owners to provide means for closing the wells when the water is not needed. Even where such precautions are taken, however, much water may be lost through defective casing, which allows leakage into shallower porous beds.

RECOMMENDATIONS.

The vital character of the problems involved in water-well pollution should lead to the following definite procedure in sinking important wells:

1. An accurate log of the well should be kept, so that the depth and character of the water-bearing formations may be known.

2. Every water-bearing layer should be carefully examined as to its thickness and the quality of the water it yields.

3. The head of water of each water-bearing layer and its relation to other water encountered should be accurately determined, so that, if necessary, contamination may be prevented by using packers and separate pipes for each water horizon.

4. The casing should be intact when the well is completed, and should be kept so in order that it may fulfill its duty in shutting out undesirable water. Its condition should be determined from time to time by suitable experiments.

5. The possible effects of defective casing should always be considered in interpreting a change in the head or the quality of the water.

6. In those States in which the geological conditions favor contamination of underground-water supplies, the examination of the well casing and the determination of the relations of separate water-bearing beds should be imposed by law on each well owner or well driller.

7. In States where flowing artesian water is obtained, laws should provide for the closing of flowing wells when they are not in use, so that the artesian basins may not be needlessly drained.

CAPACITY OF WELLS.

SIMPLE TESTS.

The testing of the capacity of a water well is the duty of the driller and is considered an essential part of the sinking of a well, especially as tests must occasionally be made while the well is being drilled. Wells sunk by percussion methods may be tested by bailing rapidly with a bailer or sand bucket, the capacity of the bailer and

the time during which the test is conducted being known. The larger wells may be tested by means of a centrifugal pump, and many small wells are tested merely by attaching a hand pump and pumping rapidly for several hours.

The proper testing of a well, however, involves also a knowledge and interpretation of the geologic structure as revealed by the boring.

In many parts of New England the rocks consist of schists, gneisses, and granites, and the structure is so complex that conditions are extremely unfavorable for procuring water by deep wells. The water supplies obtained are chiefly from the streams or from the ground water in the decayed upper portion of the crystalline rocks. Some of the drillers and many of the well owners in this region believe that sufficient water may be obtained if only the wells are drilled deep enough. But sometimes a driller who realizes the fallacy of this belief nevertheless fosters the idea in the mind of the owner and drills a well 400 or 500 feet deep into "dry" rock. The surface water drains into it, and the "test" consists in pumping accumulated surface water from a deep drill hole.

A test of this character which was conducted under circumstances that make the naming of the specific locality inadvisable is here cited, because it affords a by no means isolated example and because its mention may prevent a repetition of the trick. The well had been drilled 350 feet deep and the suction pipe was extended nearly to the bottom of the well. The well was tested by a steam pump for ten or fifteen minutes, until the surface water was exhausted, when the driller always found some excuse for stopping the engine. By the time the imaginary difficulty was overcome sufficient surface water had again accumulated in the bore hole to permit steady pumping for several minutes more. The well owner was satisfied with the test and was about to accept the well when his attention was called to the conditions. On insisting that the well be pumped continuously for several hours he discovered the source of the water and its small amount.

TESTS OF FLOWING WELLS.

Other phases of the testing of water wells have been discussed by Chamberlin. In speaking of the defective flow of artesian wells, he says:[a]

> It is possible, in perfect honesty, to make both a negative and a false test. Suppose that two porous beds, A and B [fig. 21], separated by an impervious layer, are traversed, and the testing of the first has been neglected, either because it failed to give encouraging indications or for other reasons. It is now desired to test these. Suppose the seed bag or rubber packing be placed above the upper one. Now, if both bear a water level equally high the test will be fairly made and the result will indicate their combined capacity; or, if both

[a] Chamberlin, T. C., Requisite and qualifying conditions of artesian wells: Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 160–162.

heads are at least as high as the surface at the well, the test may be accepted. But suppose that the bed A has been cut into by erosion or been reached by crevices or is otherwise defective, while the other, B, remains intact and bears an elevated fountain head. Under these conditions the water may flow from B through the bore into A and escape laterally through it, as illustrated in the figure. Now, in this case the result may be either simply negative [fig. 21] or positively false and misleading [fig. 22]. If the lateral leakage through the stratum A effectually disposed of the flow from B, and there was no leakage in the upper portion of the well, the water in the test tube would stand during the test at essentially the same height as before, and the result would be negative, merely failing to indicate a possibility that really existed. If, on the other hand, there was lateral leakage through the upper strata as well as through A, neither alone being quite competent to dispose of the flow from B, then the introduction of the test pipe would cut off the upper leakage, leaving the bed A unable to dispose of the entire flow. In this case there would be a rise of water in the tube and possibly a flow. The mischievousness of a test of this sort lies in the fact that it appears to be a true test, because it shows some result, while in reality it is false and misleading. The true test in this case can only be made by placing the packing between the porous beds A and B.

FIGURE 21.—Section of a well illustrating a negative test.

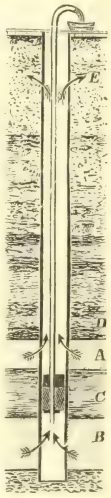

FIGURE 22.—Section of a well illustrating a partial and misleading test.

Take another instance where two porous beds, as A and B, figure 22, have been traversed. Let the packing be placed between these. Then (1), if A equals B in productive capacity, water will stand at the same height within and without the test pipe if there is no leakage in the upper beds. (2) If the failure to flow was due to such leakage, then a flow will result from B, but the additional flow which might be secured from A is lost. (3) If A has a greater head than B, and if there is no loss above, the water in the test pipe will actually be lower than that outside, as illustrated in figure 23. This may be said to be an inverted test and is less misleading than the false and negative tests, since it plainly indicates an error of manipulation. I have known such a case of reduced head as the result of an attempted test. (4) If, however, there is in this case considerable lateral waste in the upper strata, the valuable flow from A will be lost just as before the test was made, while B may give a rise in the tube, or even a flow, which would foster the impression that a fair test had been made, while in reality the greater flow has been lost. (5) If A gives a feebler flow than B, but has an equal head, the test will fail of being completely satisfactory

FIGURE 23.—Section of a well illustrating an inverted test.

only in excluding the feebler flow from A. (6) If, however, A has a lower head and is a possible means of escape from the flowage from B, then the packing has been placed at the right point and the test gives the best results.

3. In still another case let A and B represent porous beds, the lower of which is so conditioned as to drain the upper one by virtue of a lower outcrop. (1) First, if the drainage loss below is not complete, and if the packing is placed above A, as shown in figure 24, I, the result will be negative if there is no leakage in the upper strata. (2) Should there be considerable loss there it will be cut off by the tube and packing, and some rise in the tube will be the result in most cases. In either instance the result is misleading, particularly in the last, because the small rise of the water is apt to allay any suspicion as to the effectiveness of the test. The real fact, however, remains that the flow from the productive stratum is mainly lost below. (3) Suppose that the packing is located between A and B, as in figure 24, II, it will then shut off the flow from A, while that in B, because of a lower outlet, will fail to flow. Now, if there is opportunity for lateral leakage in the upper strata, the water from A will rise in the well outside of the test pipe and pass off into these open upper beds. (4) But if no such opportunity is afforded it may rise to the surface and overflow outside of the test pipe, while the water within the test pipe will probably be found to be lower than before the test was made. The proper method of testing wells known or suspected to present these conditions is to sink a simple bag of seed or other obstruction to a point in the impervious stratum between

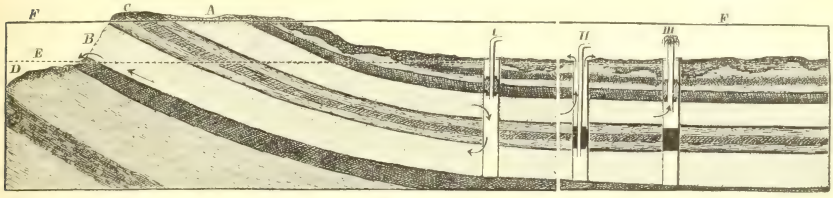

FIGURE 24.—Section of strata showing one correct and two erroneous tests.

A and B, which, when it tightens in its place, will shut off the flow below. Then a tube with packing sunk at a point above A will effectually cut off all leakage in the upper strata, and the full capacity of the water bed A will be tested.

These examples, while not exhaustive of possible cases, illustrate the nature of defective tests and the deceptive conclusions liable to be drawn from them. The remedy is manifest. Test each water-bearing stratum as it is encountered, or else vary the final tests so as effectually to exclude all liabilities to error.

STORAGE AND INFLOW CAPACITY.

Water wells drilled to a depth of less than 200 feet are commonly cased with 2-inch pipe, as it is cheap and fairly effective, but it is apt to go crooked or fail to stand the strain of driving to greater depths. Water wells more than 200 feet deep are usually made 5$\frac{1}{2}$ or 6 inches in diameter. Such wells can be drilled to considerable depths more rapidly than smaller ones, because the tools are heavy and are not so liable to break as are those used in sinking wells of less diameter. The larger pipes also make a larger reservoir for water. Usually sufficient space should be available to hold at least a barrel of water; and if the hole is of small diameter it must be drilled correspondingly

deeper, will require more casing, pipe, and pump rod, and involve a heavier lift.

The yield of a well depends on both the size of the hole and the supply. Boring is usually continued some distance below the point where water is tapped, in order to strengthen the supply, and the pump cylinders are placed some distance below the water level to allow for lowering this level by pumping.

The larger well has another advantage where a stratum that yields undesirable water must be cased off. If the well is only 3 or 4 inches in diameter at the top, it is very difficult to continue drilling with a smaller bit after casing off the undesirable water, but if the top diameter is 5⅜ inches it may be easily reduced to 4 inches and the well continued until a desirable water-bearing layer is reached. In most water wells of moderate depth, therefore, except in the matter of original cost, the larger bore is found to be the most economical.

In an oil well the size of the well has immediate bearing on the production of oil, for as the surface of the well wall varies directly with its diameter the production of the well is correspondingly greater with a larger bore. The production of a well often depends also on the size of the charge of nitroglycerin exploded at the level of the oil-bearing sands, and the use of a larger bore allows a heavier charge and insures greater production.

EFFECT OF FRICTION.

When small drilling tools are used the friction, as compared with the impact force of the drill, is greater than when larger tools are employed, for though the frictional surfaces increase directly with the diameter of the drill the proportionate increase in the weight of the drill varies as the square of the diameter. In other words, if the diameter of the drill is doubled the friction surface is also doubled, while the weight or impact force is increased fourfold. For example, if the diameters of two drills are 8 inches and 4 inches, respectively, their friction surfaces, assuming the drills are of equal length, will be in the ratio of 8 to 4, while their volumes or weights will be as 64 to 16. If the larger drill is longer than the smaller one, or if a heavier string of tools is used with the larger drill, the proportionate increase in the impact force will be greater than is indicated above, while the proportionate increase in the friction will remain the same.

Another factor in the friction problem is the steadiness of the drill in the hole. In this respect, also, the large, heavy drill has the advantage, as it is not subject to so great vibration as the small drill, and therefore produces a straighter hole.

MEASUREMENT OF DEPTH.

CABLE MEASUREMENT.

In a well that is being drilled with a standard outfit the depth is usually measured by the cable or derrick method, the distance to the bottom of the well being obtained at any time by measuring the length of drilling cable as the tools are lowered into the hole. Just as the top of the tools are about to enter the hole, a string or a strand of rope is tied to the cable at the bull-wheel shaft. The tools are lowered until this string has gone up over the crown pulley and down to the well head, then another string is tied to the cable at the bull-wheel shaft, and so on until the tools reach the bottom, the last fraction of derrick height being measured by a 5-foot stick. The number of strings tied to the cable is then multiplied by the distance from the bull-wheel shaft up over the crown pulley and down to the well head. This distance, added to the last fraction of derrick height, gives the total depth of the well.

Errors in measurement may be caused by the slipping of the string tied to the cable, by the stretching of the cable, or by miscount of the number of strings. Any one of these inaccuracies vitiates the record for scientific purposes. These errors are, of course, more likely to occur as the well becomes deeper.

TAPE MEASUREMENT.

The exact depth from the surface to the oil-bearing sands is a matter of more importance to the oil-well driller than the exact depth and thickness of each stratum passed through, because it is necessary to avoid error in selecting the position at which to place the torpedo, whose explosion is a matter of great importance in the yield of the well. Therefore, when the oil sands are reached the well is measured by a metal tape. This measurement is a delicate operation, since in some wells one-quarter to one-half mile of tape must be used, the weight of which is considerable, and even in a steel tape the stretch is sufficient to account for many errors of judgment.

The measurement of a well with a steel tape has often been found difficult, on account of the magnetized condition of the well casing, which has been produced by the jarring of the drilling tools and which causes the tape to be drawn to the casing and held there, making a correct measurement impossible. To avoid the difficulties of magnetization a copper wire or tape may be used, as copper does not respond to the magnetic influence of the casing, and by its use a better determination of the depth can be made.

BACON DOUBLE-CONE METHOD.

An ingenious instrument has been devised by Mr. J. E. Bacon for measuring the depth and thickness of water-bearing strata. This instrument is shaped like a double cone, and consists of a central brass plate, over whose edge are drawn wires fastened at each end to a center post. To one end of this apparatus a line is attached. As it is lowered into the hole a steady stream of water under known pressure is forced down the well. This acts on the brass plate and produces a certain determinable tension on the suspending line. When a water-bearing stratum is reached the loss of water into it and consequent decrease of tension on the line as the instrument passes its upper surface at once indicates its position. A reverse change of slighter value as the instrument passes the bottom of the stratum in like manner indicates this second position.

DEFLECTION OF DRILL HOLE.

CAUSES AND RESULTS OF DEFLECTION.

In beginning a well care must be exercised to make the hole perpendicular; otherwise drilling to a considerable depth is very difficult, if not impossible, because of the friction of the tools caused by increasing deflection of the hole. In order to keep the hole straight the driller may lengthen out the tools to 60 or 80 feet, the increase in length being obtained chiefly by using a long auger stem. Notwithstanding this precaution many holes go crooked, especially if the rocks are creviced, or schistose in structure, and the angle of schistosity is only a few degrees from the vertical, for the tools tend to follow the crevices or the structural planes. Under these conditions a hole may not depart greatly from the vertical during the first 1,000 or 1,500 feet, but if this depth is trebled the cumulative result may be remarkable.

Two examples of notable deflection may be cited here. One came under the writer's observation in the summer of 1905 at Casey, Ill., where a water well had been drilled 3 or 4 feet from an oil well, the drilling of which had been delayed at the depth of several hundred feet by lack of water. The driller reported very hard rock at 80 feet, and shortly afterward oil came into the water well. As the rock at that depth contains no oil it was at once suspected that the deflection of the water well had resulted in the drill penetrating the drive pipe of the oil well, and on further examination this was found to be true. The deflection in this well was in the ratio of 1 to 40, and if this had been carried to a depth of 1,000 feet, the deflection of approximately 25 feet would have been so great as to interfere seriously with deeper drilling.

The second example, furnished by a hole in South Africa, is cited in an article by H. F. Marriott.[a] The hole was bored with a diamond drill on the property of the Turf Mines, Ltd., near Johannesburg. As a result of a large number of observations in the vicinity of the property, the average dip of the rocks was taken to be 26° and the strike as due east and west. Instead of going straight down, the hole was deflected northwest from a vertical line and turned more directly toward the north against the strata as sinking progressed. Measurements by an electrical instrument show that the hole was deflected 2,185 feet away from the vertical in a N. 28° W. direction. (See fig. 25.) The actual vertical depth of the bottom of the hole, instead of being 4,802 feet as first recorded, was in realty only 3,910 feet.

These examples indicate the great value if not the absolute necessity of making an accurate survey of deep bore holes; otherwise at depths of 3,000 or 4,000 feet the true position of oil or gas sands or other mineral deposits may not be definitely known.

INSTRUMENTS FOR MEASURING DEFLECTION.

Two styles of instrument have been devised for measuring the deflection of deep holes. One accomplishes this object by means of a compass needle contained in a case filled with a paraffin or other easily melted substance. After being lowered into the hole, the paraffin is melted by means of an electric current, and when sufficient time has elapsed for the needle to assume its proper position, the current is shut off and the paraffin solidifies and holds the needle in position. Errors in using this instrument have resulted from too rapid cooling of the paraffin, and, as the instrument has to be withdrawn for each determination, the process is slow.

In determining the deflection of the South African bore hole previously mentioned, a continuously recording instrument invented by Mr. Marriott was employed. This instrument consists essentially of a strong metallic cylinder containing a resistance coil, commutator, and pivoted switch arm. As the instrument is lowered the varying inclination moves the switch arm over the commutator so as to produce a varying resistance, which is indicated and measured by a galvanometer and resistance box placed at the surface in circuit with the instrument and with several electric cells of known electromotive force. By this means the position of the switch arm on the commutator and hence the inclination of the instrument are determined. Satisfactory check readings are obtained while withdrawing the instrument.

[a] Marriott, Hugh F., Electrical devices for deep bore hole surveying: Eng. News, July 27, 1905, pp. 91–94.

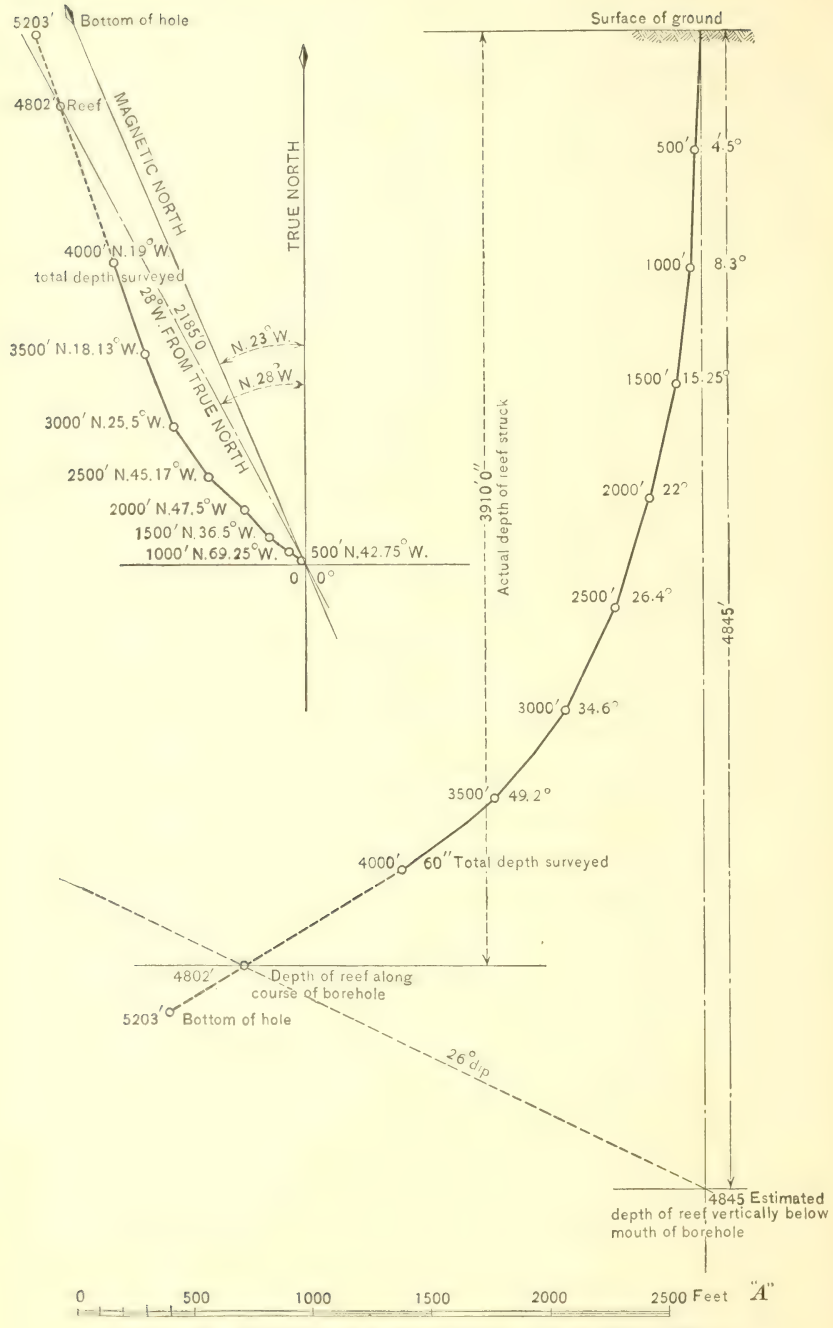

FIGURE 25.—Deflection of a diamond-drill hole in South Africa.

COST OF WELL SINKING.

Factors involved.—No other information connected with well sinking is so hard to obtain or, when obtained, is of so little general value as that relating to cost. In regions where many wells of a particular class have been sunk figures of cost may be fairly reliable; but where underground conditions are not so well known such information is more indefinite and is often withheld by drillers or contractors for business reasons.

The cost of sinking wells is determined chiefly by economic conditions, including cost of labor, material, and transportation; by the size and depth of the well; by the character of the material penetrated; and by the method of drilling employed.

If a well is sunk in a rather inaccessible locality, where fuel is scarce and labor is high, the cost will, of course, be much greater than that of a well sunk by the same method through similar formations in localities where labor and material are cheaper and transportation charges are less.

Increase in diameter of the hole not only increases the cost of sinking because of the additional material that must be removed, but it demands larger and more expensive tools and more power to operate them. The cost of each foot drilled increases rapidly with the depth, for more time is lost in changing the tools and cleaning the hole, and progress is slower because of the decreased speed at which the tools must be operated. Greater labor and ingenuity are also involved in recovering lost tools and overcoming other difficulties.

The rate at which sinking proceeds determines the time required to complete a well, and hence is an important factor in the total cost. The rate of drilling depends both on the material penetrated and the method of sinking employed. Drilling advances much slower in hard, tough rock than in more friable material, and even in plastic clays it is slow, as the material is difficult to penetrate. Quicksands also may cause trouble in some wells. With auger or jetting outfits, however, quicksands can be much more easily and cheaply penetrated than with other outfits.

As the size of the parts and the number of accessory tools for the various rigs depend on the size of the hole to be sunk and the conditions to be met, the figures of cost here presented for the various outfits must be regarded only as approximating the price of the more usual outfits at or near supply points.

Standard method.—The regular standard outfit, including rig, power, and tools, in the Pennsylvania oil fields costs from $1,700 to $3,000 or more. A 72-foot derrick with reels and ironwork costs $600 to $750. The boiler employed varies from 15 to 40 horsepower

and the engine from 12 to 30 horsepower, the size depending on the depth to be drilled; the two cost between $600 and $900. The necessary tools usually cost about $500, though fishing tools and other extras may involve an aggregate expenditure for the outfit of as much as $4,000.

The average cost of oil-well casing ranges from 40 or 50 cents a foot for 4-inch to about $2 a foot for 12-inch, though the price varies with the iron market and with the freight charges.

In the Gaines oil field of northern Pennsylvania, where drilling sometimes proceeds at the rate of 70 feet in twenty-four hours, through shales and shaly sandstones and limestones, drilling is done by contract at about 65 cents a foot, the cost of casing being additional.[a]

In the Coalinga oil district in California, where water has to be purchased and forms an extra item of expense, the average cost of a 4,000-foot well has been estimated at $7,500, divided as follows: Labor and water, $1,500; casing, $2,500; outfit, $3,500.[b] Many of the deep wells in this district, which start with a casing 11⅝ inches in diameter, greatly exceed this average cost, however.

In the Summerland oil district of California wells 6 or 8 inches in diameter at the top and about 250 feet deep are put down at a cost of about 85 cents a foot for drilling only.[c]

Portable rigs.—Portable rigs are much used for drilling water wells 4 or 6 inches in diameter. A machine capable of drilling to a depth of 1,000 feet costs about $1,100 with nontraction power, and about $1,400 with traction power. The tools for such a machine, exclusive of cables, cost $400 to $500 additional. Lighter machines, with a capacity of about 300 feet, cost about $700 with power, this amount being about equally divided between the machine and the engine and boiler. Tools and cable for such a machine cost $200 to $250 more.[d]

The rate of drilling with portable outfits varies. In shale, soft sandstone, and similar materials, 30 to 50 feet a day is a common record; in hard sandstone, 15 to 25 feet a day; and in clay and other unconsolidated material, 75 to 100 feet a day is a fair average.

The cost of drilling wells varies from 10 or 15 cents a foot in the softer materials to $1 or more a foot in hard rock.[e] In the northern Mississippi Valley 4-inch and 6-inch wells in shale and limestone cost 50 cents to $1 a foot for drilling only; in quartzite the cost runs up to $3 and $4 a foot.[f]

[a] Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 3, 1902, p. 605.
[b] Notes of Ralph Arnold, U. S. Geol. Survey.
[c] Bull. U. S. Geol. Survey No. 321, 1907, p. 65.
[d] Net prices given in trade catalogues, 1906.
[e] Statements of drillers.
[f] Water-Supply Paper U. S. Geol. Survey No. 255, 1910, p. 35.

In the hard, tough lava of eastern Washington, where in some wells only 2 or 3 feet a day can be drilled, the drillers charge $2.25 to $3 a foot, fuel and board being furnished them.[a]

The portable rig has been used in drilling shallow holes of small diameter for blasting or exploration purposes at a cost as low as 8 cents a foot.[b]

Pole-tool method.—The figures of cost given above also apply approximately to wells drilled with Canadian pole-tool outfits, for the chief advantage of the use of the pole-tool outfit in some parts of the country is its adaptability to drilling wet holes.

Self-cleaning or hollow-rod method.—Hollow-rod tools are often used with a portable machine built for cable tools, the rods and other extras costing $150 to $250 for a capacity of 250 feet. Additional rods cost 25 cents to $1 a foot, depending on their quality. The common sizes are 1 to 2½ inches in diameter.

Machines built especially for hollow-rod tools, complete with horsepower attachment, tools, and 100 feet of rods, cost from $225 for 2-inch outfits to $325 for 5-inch outfits. The price for a machine with a 5 or 6 horsepower engine and boiler ranges from $650 to $800.[c]

The cost of drilling with hollow-rod tools does not differ greatly from that with small portable cable rigs under similar conditions, but no specific figures are at hand. It is, however, usually 20 to 30 cents a foot, without casing.

California or stovepipe method.—Concerning the California or stovepipe method of well sinking, the following figures have been published. The machinery and power cost $1,500 to $1,800, and the tools and accessories $500 or more, additional; and a pair of hydraulic jacks cost $250.[d] The following tables show approximately the cost of sinking wells by this method and the cost of stovepipe casing. The latter cost, of course, varies with the price of steel.

Cost per foot of drilling wells by the California or stovepipe method.[e]

	4-inch.	5-inch.	6-inch.	7-inch.	8-inch.	9½-inch.	10-inch.
First 100 feet	$0.30	$0.30	$0.35 0.40	$0.40	$0.40– 0.50	$0.60– 0.65	$0.65
Additional for each 50-foot increase in depth	.25	.25	.20 .30	.20– .35	.20– .35	.20– .35	.35

[a] Water-Supply Paper U. S. Geol. Survey No. 118, p. 60.
[b] Statements of operators.
[c] Net prices given in trade catalogues.
[d] Stevens Institute Indicator, vol. 22, 1905, pp. 17–30.
[e] Water-Supply Paper U. S. Geol. Survey No. 137, 1905, p. 32.

Cost of riveted steel well casing in 2-foot joints.[a]

Diameter.	Gage.	Price per foot.	Diameter.	Gage.	Price per foot.	Diameter.	Gage	Price per foot.
Inches.			*Inches.*			*Inches.*		
4	16	$0.32	7	16	$0.48	9½	14	$0.75
4	14	.38	7	14	.55	9½	12	.94
5	16	.35	8	16	.55	10	16	.68
5	14	.43	8	14	.64	10	14	.78
6	16	.42	8	12	.78	10	12	.98
6	14	.50	9½	16	.65			

[a] Water Supply Paper U. S. Geol. Survey No. 137, 1905, p. 32.

At the prices given in the preceding tables a 6-inch well 500 feet deep, with casing, would cost between $750 and $1,000, assuming that the initial diameter is maintained all the way down.

The average rate of sinking wells by this method is 40 to 50 feet in a 10-hour day.

Hydraulic rotary method.—The hydraulic rotary method of drilling, like the standard method, requires heavy machinery, and the cost of outfit is consequently high. In the Beaumont field of Texas the derrick costs about $125, and the machinery, including two boilers and two pumps, costs about $3,600.[a] For wells approximately 3,000 feet deep a 30 to 40 horsepower boiler, 10½ by 12 inch single-cylinder engine, and duplex pumps, with cylinders 10 by 5 by 12 inches, are commonly used.

Water wells 400 to 1,000 feet deep and 6 to 8 inches in diameter have been put down in southern Arkansas with hydraulic rotary outfits for $2.50 to $5 a foot, including casing.[b]

In the Beaumont oil field of Texas the contract rate for sinking by this method has averaged $4 to $4.50 a foot, including casing. In this region it takes about two months to drill a well 800 to 1,000 feet deep.[c]

Jetting method.—No figures are at hand as to the cost of jetting machines, but as the main parts of the outfit are a small derrick and a force pump the apparatus is not expensive.

In southern Arkansas 4-inch wells have been jetted down to a depth of 400 feet at a cost of $1 a foot without casing; in Louisiana smaller wells have been sunk at an average cost of 39 cents a foot.[d] In the Coachella Valley, in southeastern California, 4-inch wells are sunk and cased by contract to depths of 500 and 600 feet for $1 a foot.[e] In the coastal plain of southern California wells 2 to 4 inches in diameter and usually less than 100 feet deep are sunk by this method for 30 to 40 cents a foot, the cost of casing being additional.[f]

[a] Letters from supply companies.
[b] Prof. Paper U. S. Geol. Survey No. 46, 1906, p. 110.
[c] Bull. U. S. Geol. Survey No. 242, 1903, pp. 169-170.
[d] Prof. Paper U. S. Geol. Survey No. 46, 1906, pp. 108 and 109.
[e] Statements of contractors.
[f] Water-Supply Paper U. S. Geol. Survey No. 137, 1905, p. 32.

Core drills.—Core drills are made in a number of sizes, from hand-power machines of 300-foot capacity to electric or steam driven machines capable of boring to depths of 6,000 feet.

The hand-power drill illustrated in Plate III, *A*, with accessories and 200 feet of rods, is listed at about $600, and the powerful machine shown in Plate III, *B*, with accessories and 2,000 feet of rods, is quoted at approximately $5,500.

In 1906 the market price of carbons was $85 to $90 a carat. Since 8 stones weighing 1 to 4 carats apiece are required for each bit the bits may cost as much as all the rest of the outfit.

The wear on carbons is usually 30 to 80 cents a foot, averaging 30 to 40 cents in moderately hard rock. The total costs of drilling in moderately hard material under ordinary conditions have been $1.50 to $2.50 a foot for holes 1¼ to 1¾ inches in diameter.[a]

Records of rates of drilling show an average in chert and quartz of 75 to 80 feet for a week of sixty hours; in basalt, sandstone, slate, and diabase, about 100 feet; and in limestone 150 to 200 feet.

It is claimed that the cost of drilling with calyx and shot bits is less than that with a diamond bit under the same conditions, and that cores of larger diameter are obtained.

When chilled shot are used, the consumption is one-quarter to three-quarters of a pound for each foot drilled in soft rock, and 1½ to 4 pounds in hard material.[b]

Augers.—Hand augers to be used with common water pipe as extension rods are on the market, and range in price from about $5 for 2-inch augers to $40 or $50 for 10 and 12 inch sizes. Horsepower machines capable of boring wells 100 feet deep and 40 inches in diameter are listed at about $200.

Water wells 3 or 4 inches in diameter can be bored with hand augers at a cost of 25 to 35 cents a foot without casing; wells 6 inches in diameter have been sunk at a cost of about 50 cents a foot.[c] With the Arkansas clay auger, using horsepower, wells are put down at a cost of 12½ to 40 cents a foot.[d]

Driven wells.—The cost of driven wells consists mainly in the outlay for drive point and strainer, pipe, and suction pump. The driving itself does not require expensive machinery nor skilled labor.

A 1½-inch drive point and screen costs about $2.50; 25 feet of 1½-inch pipe, about $3; and a pitcher pump, about $5; so that the cost of small driven wells should not be more than $15.

[a] Articles in mining journals.
[b] Statements in trade catalogues.
[c] Prof. Paper U. S. Geol. Survey No. 46, 1906, pp. 109–110.
[d] Op. cit., p. 95.

SUPPLY COMPANIES.

A list of the companies dealing in well-drilling machinery that have furnished information either by catalogue or by correspondence is given below. As there is unfortunately no trade journal devoted to well-drilling machinery and most of the firms handling such machinery do not advertise in the engineering journals a complete list of American firms was not obtained. It is thought, however, that companies handling all the various kinds of well machinery are represented.

List of drill manufacturers and supply companies.

Cook Well Company, St. Louis, Mo.—auger and well screen.

Cyclone Drilling Company, Orrville, Ohio—portable drilling outfits.

Ingersoll-Rand Company, 11 Broadway, New York City—calyx drill.

Keystone Driller Company, Beaver Falls, Pa.—portable drilling outfits.

Loomis Machine Company, Tiffin, Ohio—portable drilling outfits and horsepower and handpower augers.

National Supply Company, Pittsburg, Pa.—standard, hydraulic rotary, and portable oil-well outfits.

Oil Well Supply Company, Pittsburg, Pa.—standard, hydraulic rotary, Canadian pole-tool, and portable oil-well outfits.

Southern Well Works Company, Beaumont, Tex.—standard and hydraulic rotary outfits.

Sullivan Machinery Company, 42 Broadway, New York City, and Railway Exchange Building, Chicago—diamond drills.

American Diamond Drill Company, New York—diamond drills.

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UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

WATER-SUPPLY PAPER 258

UNDERGROUND-WATER PAPERS

1910

BY

M. L. FULLER, F. G. CLAPP, G. C. MATSON,
SAMUEL SANFORD, AND H. C. WOLFF

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UNDERGROUND-WATER PAPERS, 1910.

INTRODUCTION.

By Walter C. Mendenhall.

This report is the fifth of a series of collections of short papers that give brief accounts of investigations of special underground-water problems by the United States Geological Survey. The first three of these, under the title "Contributions to Hydrology of Eastern United States," covering the years 1903, 1904, and 1905, were published as Water-Supply Papers 102, 110, and 145; the fourth, which was of the same scope, appeared as No. 160 of the same series under the title "Underground-Water Papers, 1906." The four earlier volumes were prepared under the direction of Myron L. Fuller, at that time in charge of ground-water investigations in the eastern United States. The report for 1910, like its predecessors, consists of a number of short papers giving the results of special or subordinate investigations, accounts of which are not considered sufficiently important to warrant their separate publication. Most of these papers also were prepared under Mr. Fuller's direction.

In this report an attempt has been made to bring together and to discuss a number of peculiarities affecting the economic value of wells and the occurrence of water in certain special classes of rock of widespread occurrence. Most of the papers, though based on more or less local observations, deal with problems of wide application and are therefore of general as well as of local interest. In fact, the special endeavor in them has been to present scientific results that will be of interest to the geologist or engineer, the publications of the results of general investigations of the occurrence, availability, quality, and other features of the waters found over extensive areas—such as the various States and Territories and the larger artesian basins—being reserved for special reports.

DRAINAGE BY WELLS.

By Myron L. Fuller.

INTRODUCTION.

Necessity of drainage.—A certain amount of moisture is needed to grow and mature all useful plants, but too much may be nearly as bad as too little, and, except for a few plants (rice, for instance), good crops can not be had from saturated soils or from soils covered with standing water. Unfortunately many areas of our country are poorly drained. In the north are numerous swamps and lakes in depressions in deposits left by the glaciers which once covered the region; along the larger rivers are broad areas of swampy flood-plain deposits, and in the coastal plain regions of the Atlantic and Gulf States are the broad, flat, poorly-drained, and often swampy upland areas between the streams. Immense tracts of lands which have rich soils and which would, if drained, yield abundant crops, are in their present condition almost worthless. If such lands can be reclaimed they will add materially to the productiveness and prosperity of the country, so that their drainage is a problem of great importance. Some areas, such as parts of the Mississippi delta and some of its flood plains, can never be satisfactorily drained without pumping, owing to their slight elevation above the river or sea, but by far the larger part of the wet lands of the country may be drained by one or another process, although the drainage of some areas may be prohibited by the expense involved.

Methods of drainage.—Wet lands may be drained in several ways. The water may be collected in ditches and conducted by gravity to some stream. Subdrainage by tile pipe is similar in nature and results to ditching, but does not involve the loss of the space taken up by the ditches. Though tiling is laid underground, both tiling and ditching eventually carry the water away over the surface. Drainage wells, on the other hand, carry the surface water into the ground.

Ditching and tiling are the simplest methods of drainage and are employed on lands that are moderately flat, if they are not too far

removed from a stream or valley capable of taking away the water and if they are not separated from the drainage lines by ridges of too great height. The wet lands of flood plains and the swampy upland crests between rivers in parts of the coastal-plain region are particularly susceptible to ditching, by which hundreds of thousands of acres have been reclaimed. The floating steam dredge, pushing its way through the swamps of the Mississippi and other bottom lands, is a common sight.

In the uneven glaciated regions of the northern United States, on the other hand, where confused belts of irregular knolls and ridges alternating with deep depressions occur over extensive areas, the conditions are very different. In such regions most of the areas to be reclaimed are covered by relatively small ponds or swamps, which must be drained by the individual farmer rather than the community. The drainage of these ponds by ditches is also limited to a few localities where streams to receive the water are near at hand and on the same property and where the divide through which the ditch must be cut is relatively low, conditions which, unfortunately, are not common, so that recourse must be had to some other method. The method most commonly adopted is to sink a well in such a position that it will receive the drainage of the pond or wet tract and conduct it to some porous bed of sand or gravel beneath the surface. Whether or not this is possible depends on local conditions at the point to be drained, the method being by no means generally applicable. Where the conditions are favorable, however, the method is effective, especially if only a few acres of marsh or pond are to be drained.

CONDITIONS OF DRAINAGE BY WELLS.

General ground-water level.—Wherever the surface materials or rocks are porous or contain joints, fissures, or other openings, a boring passing downward penetrates a zone saturated with water, the depth to which ranges from a few feet in regions of abundant rainfall, especially where the surface is relatively flat, to perhaps hundreds of feet in deserts or in upland plateaus and other elevations adjacent to deep valleys into which the water is drained. In the regions of abundant rainfall, in which alone drainage is commonly necessary, the top of this saturated zone, otherwise known as the water table, fluctuates with seasons, rising during periods of rainfall and sinking during periods of drought. Where there is no near-by valley into which the underground waters can drain they may accumulate in the ground until they stand almost at the surface. In some areas, even on crests, water can be had by digging 3 to 5 feet. In such areas it is apparent that, if the land is not absolutely flat, as it seldom is, some of the depressions will extend below the water

level, in which case the ground water will enter the basin and form a marsh or lake. These conditions are exhibited in figure 1, which shows the relation of a pond and marsh to the water table, the normal level of which is indicated by N. The variation of the ground-water level already mentioned produces corresponding changes in the level of the water in the marshes and ponds. In very wet seasons, as when the water level is at W, the marsh may be converted into

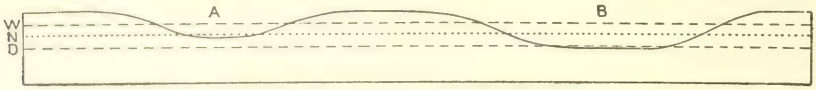

FIGURE 1.—Relation of marshes and lakes to water table. N, normal level of water table; W, level of water table in wet years; D, level of water table in dry years; A, marsh (in normal years) or lake (in wet years); B, lake (in normal or wet years) or marsh (in dry years).

a lake; whereas in dry seasons, when it has the position D, the marsh may become dry or the lake may be reduced to a swamp. Many such swamps dry up in summer, but too late to permit the planting of crops, and some are dry one year and wet the next; the uncertainty, however, is usually so great as to prevent their profitable cultivation.

Below the general ground-water level the earth is saturated with water down to the depth at which the pores become closed by the

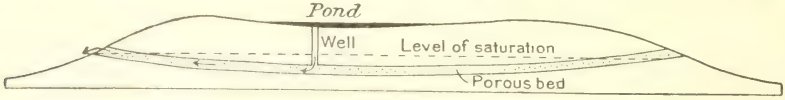

FIGURE 2.—Conditions illustrating the drainage of wells into a saturated stratum of lower head.

great pressures within the crust. Under such conditions there can be no nonsaturated layers, and drainage by wells will depend on the finding of a stratum in which the head of the water is less than that entering at the surface. Such conditions are found in basins of the form shown in figure 2.

Perched water tables.—Investigations have shown that a general ground-water level, such as is described in the previous section, seldom

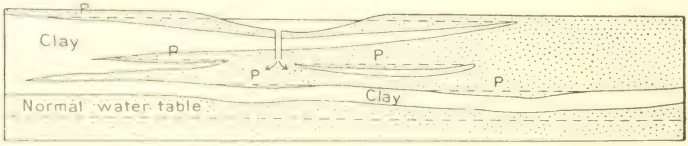

FIGURE 3.—Conditions encountered by wells sunk through perched water tables.

exists, its place being taken by local accumulations of ground water in a series of overlapping basins or strata, the surfaces of which, from their position above the ordinary water level, are known as perched water tables. Such conditions are illustrated in figure 3. One of the characteristics of perched water tables is that, except where all the

underlying beds are composed of clay or other nonporous material, there is an unsaturated zone at some point below, into which it may be possible to drain surface waters through a well, as shown in the figure.

Impervious basins.—Even where the materials are pervious and unsaturated, there are times, as during heavy rainfall, when the water, instead of sinking immediately into the ground and joining the ground-water body, collects in rivulets on the surface and flows to depressions in which, if the bottoms are above the ground-water level, the water is gradually absorbed. In flowing over the surface, however, more or less fine silt, leaves, grass, straw, and like material is picked up and carried to the depression, where it is left behind as the water is evaporated or absorbed. In the course of time a coating of muck, consisting of the silt and other materials, is formed over the bottom, which may eventually make it so impervious that the water will be retained, as shown in figure 4. The conditions are closely similar to those of the perched water tables, except that the waters are entirely on the surface and are derived directly from rainfall rather than from the ground water. Unsaturated materials into which the water may possibly be drained are nearly always present.

Flood waters.—Floods as a cause of wet lands are, like lakes in impervious basins, independent of the position of the ground water, and, as a rule, flooded lands are the result of other than local conditions. Floods cover areas which are ordinarily drained, but which, owing to their low elevation and flatness, have become submerged by the overflow of streams whose channels, because of their gentle slope or crooked courses, can not remove the water as fast as it enters. The water generally returns to the stream on the falling of the flood, although the land may be so flat that the withdrawal is slow. In some places unsaturated gravels lie beneath the surface of the flooded land and it would be possible to reach them by drainage wells, although where the water stays over the land for a long time the deposits beneath it are likely to become saturated up to the surface.

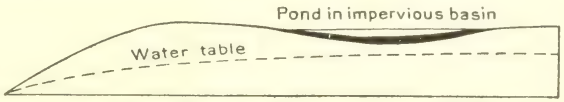

FIGURE 4.—Pond held in impervious basin above the water table.

Action of wells.—The efficiency of a drainage well depends on the difference in the head of the surface and the ground water, on the porosity or water-bearing capacity of the materials or deposits into which the water is to be carried, and on the grain of the materials. In order that the well may be effective it is necessary that the general level of the ground water must be lower than the depression to be drained, or else that the well shall strike an open passage or a deeper water-bearing stratum of low head. The material, if unsaturated, must be sufficiently porous and extensive to take up the water brought

to it by the well. If saturated, the head of its waters must be less than that of the water of the basin to be drained, a condition which generally involves a low outlet, as shown in figure 2. The grain of the material must be so coarse that the water can readily enter it and drain away, or else there must be a definite open passage for its removal. If the water is not removed it will soon rise in the well until it reaches the level of the marsh or pond and drainage will come to a standstill.

EFFECTIVENESS OF WELLS SUNK IN DIFFERENT MATERIALS.

SURFACE DEPOSITS.

The surface deposits include unconsolidated materials, such as clay, sand, and gravel, and the heterogeneous mixture of all three deposited by glaciers and known as till.

Gravel.—Ordinary gravel consists of a mixture of pebbles of various sizes with a certain amount of sand that fills the spaces between the pebbles. If the pebbles are of uniform size and spherical shape, the absorptive capacity will range from a minimum of about 26 per cent to a maximum of 47 per cent. If the pebbles are flat the porosity is somewhat less, as it is if small pebbles and sand grains occupy the spaces between the larger pebbles. The average porosity of gravels is probably between 30 and 35 per cent. The grain of most gravels is so coarse that the water enters them readily without clogging the pores, thus availing itself of practically the entire porosity. Likewise if a gravel bed is cut by a ravine or valley its waters are quickly drained away. For these reasons gravel, where its structure and location are favorable, is an ideal material into which to drain wells.

Sand.—In sand the grains are generally more or less spherical and of relatively uniform size, from which it follows that the porosity will be high. Theoretically the porosity is greater than that of ordinary gravel, which consists of a mixture of large and small grains, but owing to the arrangement of the grains the actual porosity is very similar, averaging about 35 per cent. The grain of medium and coarse-grained sands is so coarse that water will enter them freely, provided it carries but little silt to clog the pores between the grains.

Clay.—Clays are silts composed of minute particles of rocks and minerals, which may contain hardly a trace of grit. Contrary to the common belief, tests show that they are exceedingly porous, many varieties having porosities as high as 45 or 50 per cent of their volume. Notwithstanding this high porosity, however, they can not be used for drainage, as their grain is so fine that water penetrates them very slowly and with great difficulty.

Till.—Till is a heterogeneous mixture of clay, sand, pebbles, and bowlders deposited by glaciers. In some till deposits bowlders and pebbles predominate and the mixture is almost or quite as porous as gravel; other deposits of till are prevailingly sandy; and in still others clay predominates and the till is almost as impervious to water as clay alone. As a whole, however, till is fairly porous and is capable of taking up considerable water, especially in its more sandy and gravelly portions, so that it affords a means of drainage by wells.

ROCKS.

In unconsolidated deposits such as those just described the spaces between the grains are unfilled. In most rocks, on the other hand, there are relatively few open spaces, even in rocks formed from sand, gravel, or clay. This compactness is due to the cementation of the rock by mineral matter deposited between the grains. Sands and gravels, which originally had porosities of 35 per cent, have only10 to 15 per cent after they have been consolidated into sandstone or conglomerate, and the porosity of slate is only about 5 as compared to 50 per cent in clay like that from which slate is formed. In the crystalline rocks the porosities are still smaller.

Conglomerate and sandstone.—As indicated above, sands and gravels retain porosities of 10 to 15 per cent after they have been consolidated into sandstone and conglomerates, and this makes them capable of taking up a considerable amount of water. The facility of entrance of the water, however, is greatly reduced by the consolidation, owing to the partial filling of the pores by cement, and it becomes necessary to guard carefully against clogging. Drainage into sandstones is said to have been successful in Michigan, and several wells in St. Paul and Minneapolis carry refuse into the porous St. Peter sandstone.

Slate and shale.—Both the small porosity of slate and shale, which, as stated, is only about 5 per cent, and their compactness of grain prohibit their use for drainage.

Limestone.—Limestone, like slate and shale, as a rule is of very low porosity, averaging about 5 per cent. The body of the rock is therefore of little or no use in drainage. Usually, however, limestones have more or less well-defined and open bedding planes and vertical breaks or joints along which water can move, as well as irregular tubular channels due to solution. Where not too far removed from valleys or depressions into which the water from the openings can flow, limestones may afford satisfactory drainage, for a well sunk into limestone is almost sure to encounter an open crevice of one type or another within a moderate distance of the surface. Wells sunk into limestone have been used for the disposal of sewage in Kentucky, Georgia, Florida, and possibly other States.

LOCATION OF DRAINAGE WELLS.

The best location for a drainage well is at the center of the marsh or pond to be drained, since the natural drainage is toward this point, but drilling in this place may be very inconvenient, owing to the presence of water. It may therefore be less troublesome to sink the well at some convenient point on the edge of the pond or marsh where the water can be kept out by a small earth dike while the inlet is being constructed. By this method the mouth of the well can be set as low as needed at the start and advantage taken of the extra head thus afforded. Ditches should be dug to this inlet and extended and deepened as the water is lowered until the entire area of the pond drains toward the well.

CONSTRUCTION OF DRAINAGE WELLS.

METHODS OF SINKING.

The methods of sinking wells differ greatly according to local practice and the nature of materials to be penetrated.

In rocks the standard churn drill and the diamond and calyx drills may be used, but the cost of the last two is prohibitive in drainage projects, and the churn drill, operated either from a derrick or a portable machine, is practically the only outfit used. In unconsolidated deposits also the churn drill may be used, but where no hard material is to be encountered the tube is more commonly driven. A hydraulic jet forced down an inner tube and rising between it and a larger outer tube is also used in sinking wells in loose deposits. Rigs in which the well is sunk by rotating a pipe fitted at the bottom with a saw-toothed steel shoe (usually in connection with a water jet) are also used, especially in the South. The cost is about the same with all methods, and all give about the same results, except that in the shoe method the water used to raise the drillings is used over and over again until it becomes a thick sludge which tends to clog the pores of the materials penetrated. Since in drainage wells it is very desirable that these should be kept open, the method is not to be recommended. Otherwise the rig which comes handiest may be used.

CHARACTER OF INLET.

Usually the top of the casing is left by the driller just as it was sunk, the condition when the water is admitted being as shown in figure 5. This is a very poor form of intake where the water enters rapidly, owing to the constriction of the water column, which, as shown in the figure, occupies only 50 to 75 per cent of the pipe. With a bell mouth, such as is shown in figure 6, nearly double the amount of water is taken in under ordinary conditions. This difference in

the rate of taking the water is of great importance if time is considered, since a bell-mouth well, other things being equal, will drain a pond or swamp in about one-half the time required by the others. It has the disadvantage of being somewhat troublesome to construct where only the conveniences of a country blacksmith's shop are available, and it need not be used when no haste is necessary, for the regular casing will give the result desired. In figure 6 the diameter of the pipe is D; 0.62 times the diameter is the length at the end which is enlarged; 1.25 times the regular diameter is the diameter of the bell-mouth; and 1.62 times the diameter is the radius of curvature of the expanded end.

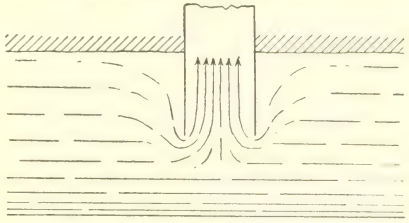

FIGURE 5.—Mode of entrance of water into ordinary casing.

PROTECTION OF INLET.

Many of the ponds and marshes to be drained contain floating vegetable matter—leaves, twigs, grass, water plants, and slime—which is rapidly drawn toward and into the well by the current set up by the indraft of water. As this material would soon clog the well it should be kept out by surrounding the well mouth with a brick or other curbing provided with screen-protected holes, as illustrated in figure 7, or by means of some other effective screen.

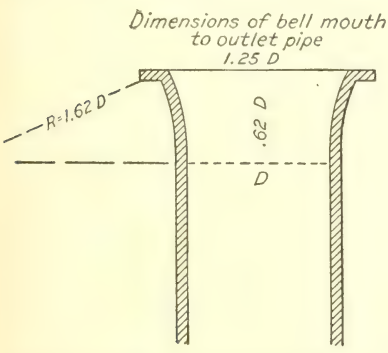

FIGURE 6.—Bell-mouth intake to drainage well.

CAPACITY OF DRAINAGE WELLS.

RELATION OF CAPACITY TO CHARACTER OF INTAKE.

The relation of the capacity of the well to the character of the intake has already been noted, it being pointed out that the capacity of a bell mouth, such as shown in figure 6, is nearly double that of a well having only the ordinary casing. The capacity of a well is also related to the character of its protection, screens of sufficient area and porosity to admit an adequate volume of water and at the same time keep out débris being essential.

RELATION TO EFFECTIVE HEAD.

In a well like that shown in figure 7 the theoretical head is the difference of level of the ground and the surface waters, or the distance from A to the water surface of the pond. If the material at the bottom is not very porous and the water enters slowly, the entire pipe will be filled, and the actual effective head, or that forcing the water

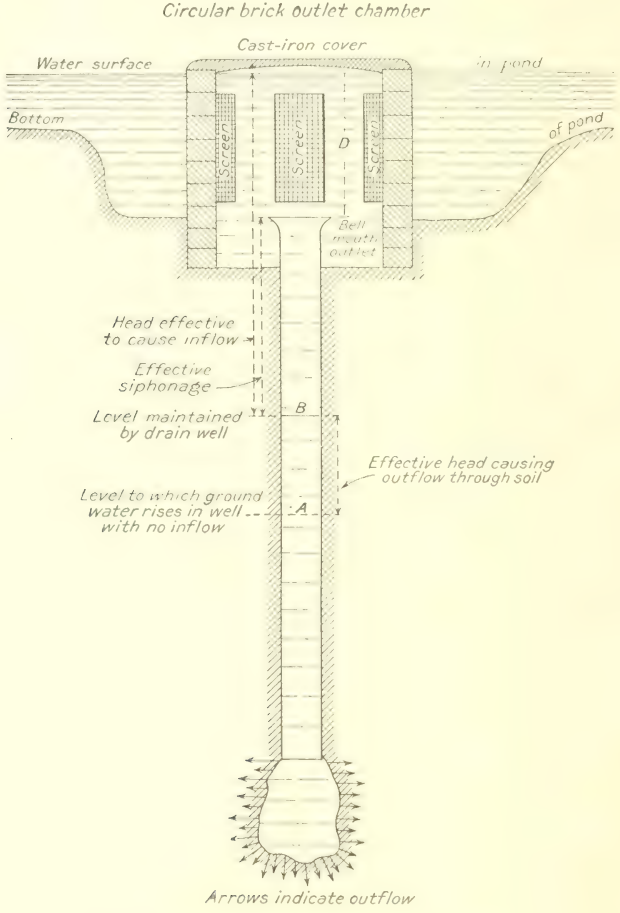

FIGURE 7.—Protection of intake of drainage well.

into the ground, will be the same as the theoretical head. If, however, the water is taken off rapidly into the ground, a sort of whirlpool will be formed, as a result of which the pipe is no longer completely filled, and the entire inflow may be only just sufficient to raise the water level from A to B. In this case the effective head forcing the water into the soil is the distance from A to B instead of from A to the surface as before.

RELATION TO SIPHONAGE.

In regard to siphon action in drainage wells R. E. Horton has made the following statement: [a]

> In a well having a tight casing and a proper entrance the inflow will be augmented by siphonage or draft-tube action, the water being forced down by atmospheric pressure in a manner the inverse of the action of a lift pump. If there be free discharge at the bottom and if the well be over 33 feet deep, then the maximum possible draft-tube head of 32.8 feet may be available.
>
> Unless the ground-water horizon is at exceptionally great depth, however, it will probably happen, as has been observed in practice, that the discharge head, h, required to take care of this large inflow of water, will cause the water level B to rise within much less than 32.8 feet of the surface, limiting the siphon head and dividing the total static head from A to the water surface of the pond in such a manner that the inflow head will just supply such a quantity of water as can be forced out of the bottom of the well by the remaining or discharge head. In any event the gain in capacity and rate of drainage which will result from siphonage will be very great; for example, with a pressure head D of 1 foot over the inlet, the discharge would be nearly doubled by the addition of 3 feet of effective siphonage and nearly trebled by the addition of 8 feet of effective siphonage.

AREAS DRAINED.

The area which can be drained depends on a great variety of factors. Under some conditions, such as those illustrated in figure 4, it is simply the visible water of the pond or marsh which must be considered, but under the conditions represented in figure 3, not only must the visible water be taken into account, but also the much more extensive area of tributary ground water. The pond can not be drained until the level of the ground water is reduced to a point below its bottom. It is therefore apparent that an extensive marsh can be readily and quickly drained if its bottom is above ground-water level, but that even a very small marsh that is continually replenished from the ground water can be drained only with great difficulty.

Again, the effectiveness of the drainage will depend to a considerable extent on the excess of head of the pond waters over those in the ground. If the difference is slight the drainage will necessarily be slow and difficult. The porosity of the bed into which the water is drained is also an important factor in determining the effectiveness, for unless the water is taken up and removed the well will be a complete failure.

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[a] The drainage of ponds into drilled wells: Water-Supply Paper U. S. Geol. Survey No. 145, 1905, p. 35.

Some actual examples of the areas drained, as cited by R. E. Horton,[a] are presented below:

Areas drained in Michigan by wells.

Owner.	County.	Diameter of well.	Land drained.	Pond or marsh drained.
		Inches.	*Acres.*	*Acres.*
Fred Watkin	Jackson	.....	35	2½
T. Eggleston	do	3	.....	2½
C. I. Moe	do	3	10	.....
V. R. Horton	do	4	60	.....
W. H. Hartwell	Calhoun	4	40	.....

The time taken for drainage differs with the area drained and with differences in conditions. A pond covering 2 or 3 acres can be drained in a few months; if begun in March, the drainage will be completed in time for planting in May.

If the well enters an open cavity, as in limestone, the drainage is much more rapid and the area drained may be much larger than with other materials. In many drainage wells the capacity of the intake pipe is the only limiting factor.

COST OF WELLS.

The cost of wells varies according to the size and type of well, depth and length of casing, character of screens, if any, and other factors. Local practice also has much to do with the cost; a well at one point may cost twice as much as a well at another, even if the two wells are in adjoining counties. A drainage well of about the minimum practicable diameter—4 inches—will cost from 75 cents to $1.25 or more a foot, $1 being perhaps a fair average. In addition to this there will be a charge of about 25 cents a foot for casing. Screens for a 4-inch well cost from $4 to $8 a foot, according to material, method of construction, and size of mesh.

CAUSES OF FAILURE.

The causes of failure of drainage wells include what may be termed primary causes (or those dependent on the underground conditions, including the character of the materials and the hydrostatic conditions), and secondary causes, or those arising subsequent to the sinking of the well and independent of the underground conditions.

PRIMARY CAUSES.

Head of ground water.—Of the primary or original causes of failure the most common is probably the deficiency in head of the waters of the marsh. In many places the water in the drainage well stands so

[a] Loc. cit., pp. 30-39.

nearly at the level of that in the pond or marsh that little pressure is exerted by the ponded water and the inflow into the well is either feeble or lacking. In some wells the ground water is even under sufficient pressure to lift it above the level of the pond or marsh, and the well must be shut off to prevent further flooding of the depressions.

Absorptive capacity.—Next to the head of the underground waters, low absorptive capacity of the material encountered by the well is the most common cause of failure. Nearly all unconsolidated materials are porous, even clays having as high as 40 to 50 per cent of pore space, but many of them, owing to fineness of grain, so resist the entrance of water that they are unavailable for drainage. Another cause of failure arises from the pocket-like character of some of the sand or gravel layers, which are so small in extent that they quickly become filled to their full capacity, if they were not full at the start.

Rise of ground water.—Still another cause of decline and eventual failure lies in the lifting of the ground-water level as shown in figure 8. In this diagram A B represents the normal or original ground-water level. When the water is first turned into the well it is rapidly absorbed and the water table rises in the vicinity of the well. As the water continues to pour into the bed it becomes saturated to the

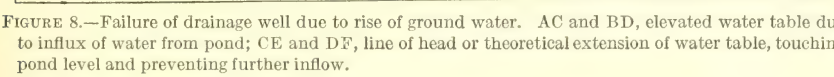


FIGURE 8.—Failure of drainage well due to rise of ground water. AC and BD, elevated water table due to influx of water from pond; CE and DF, line of head or theoretical extension of water table, touching pond level and preventing further inflow.

top and all further escape must be laterally toward A and B. At first the slope is fairly steep, but it gradually becomes more and more gradual, taking the form A C D B, the friction at the same time greatly increasing and acting as a restraint to the entrance of further water. If the friction becomes equal to or greater than the head, the inflow will stop.

SECONDARY CAUSES.

Obstruction of well mouth.—Most of the ponds or swamps to be drained contain much aquatic vegetation—reeds, grasses, etc.—which is torn up by ice or otherwise uprooted or broken and ever ready to accumulate at the well and to choke the pipe or clog the screens with which the well mouth is protected.

Clogging of receiving materials.—If coarse matter, such as leaves, grass, and weeds, are allowed to enter the well, the sand, gravel, or other material into which the water is drained will soon become clogged. The entrance of such matter is easily prevented, but the difficulty due to the clogging of the pores between the finer grains by silt is very serious in wells sunk in the finer materials.

Clogging of well screen.—The clogging of the screens is even more serious than the clogging of the sand itself, inasmuch as the screen, in order to keep it out of the well, must be of a mesh finer than the sand, and thus is still more likely to become clogged.

Entrance of quicksand.—If the wells are without screens quicksands may enter through the open bottom and gradually become compacted into a relatively impervious mass that fills the bottom of the well and greatly hinders the exit of the water.

Caving of the materials.—If the materials penetrated are fairly stiff, even if they are not consolidated, it is not uncommon to leave the well uncased. In such uncased wells, however, the material afterwards may become softened or loosened and cave in and clog the well, damaging or ruining it for purposes of drainage.

REMEDIES.

The procedure in case of failure will depend upon the probable cause of the difficulty as determined by a careful investigation of the conditions. If the stratum reached by the well is of low porosity or low absorptive capacity little can be done with it, and a lower bed should be tried. If the head is high enough to lift the underground water to the surface there is usually no remedy, as lower heads will rarely be found in underlying rocks. If the stoppage of drainage is due to the rise of the ground water or to the filling of pockets lower beds should be sought.

Of the secondary causes of failure the clogging of the well is the most common. The entrance of coarser floating matter can readily be prevented by proper screening, but the fine silts, which are hardly less objectionable, can not be so readily excluded. Much of this silt is washed in by the rains and settles in a few days or weeks, so if provision is made for closing the well until the water has cleared much difficulty will be avoided.

If the silt finds access to the well and clogs the pores of the sand one or another of several treatments may be adopted. Heavy pumping for a few hours may serve to draw back and remove some of the silt which has accumulated in the sand, leaving it free to take up water once more, or additional pressure may be brought to bear on the material at the bottom of the well by means of a water jet forced down by a steam pump, the object being to break up the film of silt which has collected on the surface of the material at the bottom of the well and to force it back and disperse it throughout the body of the deposit. For this purpose the "steam jet," used in drilling in Ohio, may be employed to advantage. By this apparatus highly heated steam forced into the material at the bottom of the well converts the water it contains into steam, causing an explosion that loosens the surrounding deposits.

USES OF DRAINAGE WELLS.

The foregoing discussion has dealt chiefly with wells sunk in unconsolidated materials, mainly to reclaim small ponds and marshes for cultivation. There are, however, several other important uses of drainage wells, some of which are considered in the following paragraphs.

MARSHES AND SWAMPS.

Marshes of drift regions.—Marshes have been drained in several northern States, especially Indiana, Michigan, Wisconsin, and Minnesota, the surfaces of which are in large part covered with deposits of gravel, sand, clay, and other unconsolidated material left by the glacier in the form of irregular hills and ridges, between which are numerous deep undrained depressions containing ponds or marshes. The conditions and results differ but little in the various States, the figures given for Michigan on page 16 being typical. Depressions on the higher lands can as a rule be successfully drained by wells, but many wells sunk in the deeper basins or on lower grounds strike flowing waters instead of waters of low head.

Coastal-plain swamps.—A special type of swamp is found on the upland crests between the streams of the Atlantic coastal plain in certain of the Southern States. These upland surfaces, which represent old sea bottoms, have been uplifted intact, retaining the same flat stretches and shallow depressions that marked them when originally deposited. Over these surfaces swamps, most of them characterized by heavy timber, have been formed. In general they are too extensive to be drained by wells, even if the head of the underground waters were not, as it frequently is, too high. Fortunately many of the streams in this region have cut deep valleys to which it is feasible to conduct the water by ditches.

River-bottom swamps.—River-bottom swamps are generally not like basins but are simply low tracts that border large rivers and are subject to overflow, the water standing on them temporarily rather than permanently. While the river is in flood there is of course no possibility of draining one of these swamps, for the water will come in from the river as fast as it is removed, and even after the river goes down much water is still held on the flat lands. The area of many of these river-bottom swamps is too extensive to permit their drainage as a whole. Some of them are underlain by beds of gravel or sand which are not completely saturated, and the surface water could be carried into these beds by wells, but except for small areas that could be separated from the surrounding wet lands by dikes, their drainage by wells would be impracticable and, in view of the cheapness of well-drained land in the same region, it is seldom desirable. Ditching is practicable in most of these swamps and in some of them is being pushed rapidly forward.

Sunk-land swamps.—In southeastern Missouri, northeastern Arkansas, and western Tennessee there are numerous depressions due to local sinking of the land caused by the New Madrid and other earthquakes. The largest of these is Reelfoot Lake, in northwestern Tennessee. This lake is 20 miles long and 5 miles broad, and covers land which, if reclaimed, would afford agricultural soils of the finest quality. The drainage of this lake is now under consideration, but the work must be done entirely by ditching, the water table being too high for drainage by wells.

Extensive sunk-land marshes also occur along Varney and other rivers in Missouri and St. Francis River in Arkansas, and many small basins or sloughs lie in the woods in northeastern Arkansas. Marshes near a river are controlled by river level, and the drainage of most of them is impracticable. A smaller slough can be drained by wells when the region in which it lies is occupied by settlers.

PONDS.

The drainage of ponds in Michigan by wells has already been noted (p. 16). In Minnesota very similar results have been obtained at several places, and in Wisconsin, Indiana, and other States where the surface deposits are of a similar type drainage wells have been successfully employed. In these States most of the wells drain into beds of sand and gravel in the drift, although a few of them in Michigan are said to drain into sandstone, and some at Minneapolis and St. Paul discharge refuse into the St. Peter sandstone. In Georgia and Florida the receiving bed of a number of wells is limestone. By a drainage well sunk at Quitman, Ga., 1,500,000 gallons were drained from a pond in a few hours. In Virginia, Kentucky, Tennessee, Indiana, and other States in which limestone occurs it is a common practice, it is said, to dig or drill for the purpose of carrying the water out of sinks into the underlying limestone.

CELLARS.

Cellars have been drained by wells at Minneapolis, St. Paul, Hampton, Blooming Prairie, Bricelyn, and Geneva, and doubtless at other places in Minnesota, as well as in other States where the surface is underlain by porous beds of sand or gravel or by limestone with open crevices.

INDUSTRIAL WASTES.

Little is said by owners of borings into which industrial wastes are being turned, but it is probable that such drainage is practiced in Minneapolis and St. Paul and in certain limestone areas in Georgia and Florida. Creamery waste products are disposed of in this way in some country towns.

SEWAGE.

In Kentucky, Georgia, Florida, and other States sewage is at many places poured into borings in limestone. Among the cities in which there are public or private sewage wells are Georgetown, Ky., and Orlando, Ocala, Live Oak, Gainesville, and Lake City, Fla.

POLLUTION OF GROUND WATER BY DRAINAGE WELLS.

NATURE OF POLLUTION BY WATER TAKEN FROM DIFFERENT SOURCES.

Drainage wells have been successfully used in many places and may be multiplied to advantage, but they are likely to pollute the ground water.

Ponds.—The water of ordinary small ponds on a farm is not of good quality. Usually shallow, the water becomes much heated and contains vegetable growth, which gives it a decided taste and color. Cattle may drink from the pond or stand in its waters, polluting it in various ways. A drainage well adds the organic matter and pollution to the ground water, materially lowering its quality.

Marshes.—What has been said of ponds applies also to marshes. Swamps contain even more organic matter than ponds, and consequently their drainage into the ground water is a source of greater pollution from vegetable though not from animal refuse.

Fields.—Waters derived from fields are generally somewhat polluted. In running down slopes they carry along decaying vegetable matter; in cultivated fields where manure or other fertilizer is used and on land where cattle are pastured they gather much more objectionable pollution and carry it to the ground water through drainage wells.

Cellars.—Water in cellars has fallen as rain in the yard or vicinity and seeped down through the soil into the cellar, perhaps made foul by privy wastes, slops, or other pollution. It is needless to say that such water does not constitute a desirable addition to the ground-water supply when it is conducted into the ground through a drainage well.

Wastes.—Most industrial wastes are obnoxious in taste and odor, and some of them are deleterious to health, but generally not so dangerous as water taken from the farm and barnyard. Nevertheless, if they are carried into the ground water by a drainage well, they will unfit it for domestic uses.

Sewage.—The drainage of sewage into the ground water may spread disease to all who drink the water.

EXTENT OF THE POLLUTION.

The distance to which contaminating material will pollute ground water will differ greatly under different conditions. If the polluted water is added to saturated sands or gravels, its effect will not extend to a great distance, usually not more than a few hundred feet, owing to the slowness of movement of the water. If added to an open sand, the polluted water may spread to a considerable distance. In general, however, in such material the area affected is not likely to be much if any greater than the area drained. The extent of the pollution also depends on the amount of water introduced, the water from a pond or marsh spreading much farther than that from a cellar or cesspool. It is fortunate that the most dangerous sewage introduced into sand or gravel spreads but little as compared with the relatively harmless water from ponds.

If a drainage well enters limestone, the conditions are wholly different. The polluted water or sewage enters an open passage in which it may be conducted for a long distance without dilution or purification. A public well that encounters such a passage may communicate typhoid fever to hundreds of persons, even if the well is miles from the source of contamination.

RECOMMENDATIONS.

1. The emptying of sewage into drainage wells is very dangerous and should be avoided.

2. The drainage of industrial wastes into borings is objectionable if not dangerous, and the practice is to be condemned.

3. The drainage of cellars into wells is objectionable in towns where near-by wells must draw on the ground water into which the cellar waters are carried. In the country the practice is not objectionable if the water is carried through a tight casing to a bed lower than that which supplies the local water wells or to a higher bed if the water wells are tightly cased through this bed and through a thickness of impervious material sufficient to prevent any possibility of contamination.

4. The drainage of most ponds and swamps into wells is unobjectionable, for they are far from houses and from wells that supply drinking water. The movement of ground water is normally away from rather than toward the houses, the addition from the pond serving, at the worst, to back up rather than to reverse the movement. Moreover, water does not spread far underground. On the whole the drilling of wells for draining swamps and ponds should be encouraged, but the usefulness of the wells is limited to ponds covering a few acres and to basins not exceeding in extent 75 acres.

THE FREEZING OF WELLS AND RELATED PHENOMENA.

By Myron L. Fuller.

CONDITIONS OF FREEZING.

Region affected.—Throughout many of the Northern States much trouble is caused by the freezing of wells, not so much with the shallow dug wells as with the deeper drilled ones. Many wells in the North can be kept in use during the winter only with the greatest difficulty, so that the determination of the cause of the freezing and of means for its prevention is of great practical importance.

Open wells.—In open wells, including in this class the dug wells not provided with covers, the cold air—often many degrees below zero—is free to enter and displace the air of the wells, which, owing to its contact with the water and the unfrozen earth, is generally considerably warmer. Under such conditions, although the temperature of the entering air is somewhat modified by mixture with that already in the well and by contact with the walls, freezing often occurs at considerable depths, and the well is rendered useless during the continuance of cold weather.

Covered dug wells.—In dug wells protected by covers there is generally little trouble from the freezing of the water unless it happens to stand very near the surface. Although few well coverings are tight enough to exclude the cold air, it penetrates so slowly that the temperature in the well, owing to the warmth given off by the earth and the ground water, seldom reaches the freezing point. In some wells, however, where open, water-free gravels occur above water level, much trouble is experienced.

Driven wells.—In the simpler type of driven wells, consisting of a single continuous casing, or of double tubes, both of which are carried below the ground-water level, little or no trouble is caused by the freezing of the water in the well, except, perhaps, when its level is very near the surface. The amount of cold air entering through the pump is insignificant, and there is no material circulation of air in the surrounding materials, and therefore no adequate cause for freezing.

Drilled wells.—Most of the wells subject to freezing are drilled or double-tube driven wells in which the inner or pump tube is carried below the outer casing, stopping in some porous stratum (figs. 10 and 11), or wells drilled in limestone or other rocks that contain open solution passages (fig. 12). The cause of freezing in these wells is discussed on pages 29 and 30.

Pumps.—Pumps are certain to freeze if the cylinders are near the surface, as the water left in the valves and box after pumping freezes before it can drain back into the well. Where the cylinder is placed at a considerable depth, however, this difficulty is avoided, except in what are known as the drilled wells, just noted. It is therefore the nearly universal practice to set the cylinder at as great a depth as possible and where practicable to surround it with tightly packed earth to shut out the air.

Character of material penetrated.— An investigation by F. G. Clapp of the wells of Maine, a large part of which are in granites, slates, shales, and other hard rocks that are free from openings, showed no instances of deep freezing. In Minnesota, North Dakota, and Nebraska, on the other hand, large numbers of wells that penetrate porous deposits or cavernous limestones freeze every winter. In Wisconsin and Michigan freezing, though less common, occasionally occurs, especially in some of the wells in the porous gravelly hills and ridges. Even in Pennsylvania freezing, apparently due to the same causes, occurs in oil wells at depths of thousands of feet. In States farther south, especially in Iowa, Missouri, Kentucky, and Indiana, wells occasionally freeze, both those in the porous surface deposits and those in limestones.

ATTENDANT OR RELATED PHENOMENA.

The phenomena attendant on the freezing, apparently due to the same or similar causes, include the indraft and outdraft of air that produces sucking and blowing wells, changes in the character of the water, fluctuation of the water level, and changes in the discharge of flowing wells. Each of these is not only of great interest to the owner of the well or to the driller, but presents an economic problem of practical importance.

Blowing wells.—Wells that emit currents of air from their mouths are called blowing wells. Blowing is not confined to drilled wells, but is noted in many dug wells, the air escaping through cracks or other openings in the covers. It was reported to the writer that the current passing out through the knot hole in the cover of one well was strong enough to lift a hat several feet into the air. At some times the whistling of the escaping air through the planks or pipes can be heard for several rods; at other times the current is strong

enough to operate small whistles whose sound is loud enough to be heard for a mile or more in still weather. In some wells a dull roaring sound is heard as the air rushes through the casing; in other wells the air can be heard bubbling through the water.

Breathing wells.—In most blowing wells the blowing is not continuous but alternates with sucking; such wells are more properly known as breathing wells. Probably most of the "barometer" or "weather" wells are of this class, although the indraft is usually less rapid and less conspicuous than the outdraft, and in warm climates, where freezing never occurs, may be overlooked. Its presence is, however, abundantly demonstrated. (See p. 26.) Even if no indraft is observed, it is noted that the blowing is weak or ceases at times, so that there is a rhythm in the movement of the air. In humid regions the blowing is, as a rule, most marked before rain storms, and the sucking or indraft of air occurs in clearing weather after a storm. In other words, the blowing occurs during periods of low barometer and the indraft occurs in periods of high barometer. The blowing may be associated with some particular direction of the wind, as would be expected from the fact that the direction of the wind in rain storms is different from that prevailing in clear weather. Some wells show fluctuations with very small changes of barometric pressure, even with the diurnal changes, blowing at times of low pressure, as at 3 a. m. and 4 p. m., and sucking at times of high pressure at 10 a. m. and at 9 p. m. In some wells there is a noticeable "lag" in the phenomena, the blowing and sucking continuing an hour or more after the limits indicated.

Sucking wells.—Wells that suck in air at times are common, but those with continuous indrafts are very rare. Two such "sucking" wells have, however, been reported in Tertiary limestone near Boston, in southern Georgia. Where indraft alternates with outdraft the movement has a direct relation to barometric changes, but where the indraft is continuous no such relation is observed, the phenomena apparently being independent of barometric pressure. In the wells noted above the air is sucked in by streams of water running in caverns in the rock.

Fluctuation of water level.—In many parts of the country the water level in certain wells rises and falls with changes of weather, being highest in periods of low barometer and lowest when the barometer is high. In some wells the difference amounts to several inches, and a well that must be pumped in clear weather may flow during storms or when the wind blows from a certain direction.

Variation in discharge.—Some flowing wells discharge only during periods of low barometer. Others flow with greatly increased volume at such times, the effect being especially marked in wells of large diameter that flow when they are only a little below their highest

level or maximum head. In such wells the discharge may be increased several hundred per cent during periods of low pressure.

Changes in character of water.—Most drilled wells yield perfectly clear water after they have been in use a short time, but although the water is ordinarily clear, it becomes cloudy or milky on the approach of storms and occasionally it becomes bright yellow or deep red during periods of low barometer. Examination of the water shows that its milkiness is caused by a small amount of suspended silt or clay and the yellow and red colors by suspended fine particles of iron oxide (yellow and red ocher). The presence of iron oxide makes the water unfit for use.

DISTRIBUTION OF PHENOMENA.

The phenomena described are of widespread occurrence. Blowing wells are especially common. The following list is based in part on data furnished by Samuel Sanford, of the Bureau of Mines.

Localities at which well phenomena have been noted.

Blowing and breathing.

States.	Number of localities.	Depth.	Material.	Age of material.
		Feet.		
Arizona	One.			
Arkansas	Several	a 100	Limestone	Paleozoic.
Indiana	One.	120	Sandstone	Do.
Iowa	do	70	Gravel	Pleistocene.
Louisiana	do	80	Sand	Tertiary.
Michigan	do		do	Pleistocene.
Minnesota	Many	50–150	Sand and limestone	Pleistocene and Paleozoic.
Missouri	do	a 170	Limestone	Paleozoic.
Nebraska	do	a 1,000	Sandstone, gravel, and sand.	Cretaceous, Tertiary, and Pleistocene.
New York	Several	a 150	Gravel and sand	Pleistocene.
Oregon	One.	a 360	Sand and sandstone	Tertiary.
South Carolina	do	120	Sand	Cretaceous.
Texas	Several	a 300		
Washington	do	a 500	Lava beds	Tertiary and Pleistocene.
Wisconsin	One.	a 100	Sand	Pleistocene.

Continuous indraft.

Georgia	Two	100–150	Limestone	Tertiary.

Variations of head and flow.

Michigan	Many	25–200	Drift	Pleistocene.
Minnesota	do	35–150	do	Do.
Wisconsin	Several	56–150	do	Do.

Change in character of water.

Minnesota	Several	37	Drift	Pleistocene.

a Depth of deepest well here listed for the State.

CAUSES OF FREEZING AND ATTENDANT PHENOMENA.

GENERAL CAUSE.

A study of the phenomena as a whole shows that they are only casually related to changes of temperature or of wind direction, but that they agree very intimately with barometric changes, the relation of the blowing to storms being recognized by nearly every owner of a blowing well. On the one hand, freezing, indraft of breathing wells, low water level, small discharge and clear water all occur in clear weather during periods of high barometer; on the other hand, the thawing of the well, the melting of the surrounding snow, blowing, high head, strong discharge, and milky or discolored water occur during periods of low barometer. This association, which is constant, together with the fact that the results are exactly what would be expected from barometric fluctuation, leaves little room for doubt that this is the general cause of the phenomena.

CAUSE OF FREEZING.

The freezing of wells seems to be due to the indraft of cold air at periods of high barometer, the air passing down the well (see p. 29) and freezing the water. When, on a change of weather, the direction of the air current is reversed the well thaws and the snow about the well mouth melts.

CAUSE OF FLUCTUATIONS IN WATER LEVEL OR FLOOR.

The water in many deep wells is under more or less hydrostatic pressure, which is opposed by the pressure of the air, the level at which the water stands representing the result or the balance of the two forces. If the pressure of the air is lessened and the hydrostatic pressure remains the same the water level in the well will rise, and if the atmospheric pressure increases the water level will fall. In some nonflowing wells the increased head will cause the water to flow; in flowing wells it increases the volume of discharge.

CAUSE OF CHANGE IN CHARACTER OF WATER.

As low air pressure causes increased discharge in certain flowing wells, and as increased discharge produces increased velocity of the water both in the well and in the material from which the water is derived, it often happens, where this material includes more or less silt which is too coarse to be affected by ordinary currents, that quantities of silt are loosened under the increased velocity and taken up by the water, producing milkiness. Iron oxide may be precipitated in the earth from chalybeate waters, although it may not ordinarily be present in amounts large enough to be noticeable in the

water drawn from a well, but during periods of low barometer this oxide is disturbed in much the same way as is the silt, and mixes with the water as a yellow or red precipitate, rendering it unfit for use.

In wells that do not flow occasional turbidity is more difficult to explain, but the motion of the ground water tapped by these wells is no doubt affected by an increase of discharge at places of constant outlet—an increase caused by change in barometric pressure—and as the phenomena occur under identically the same conditions it is

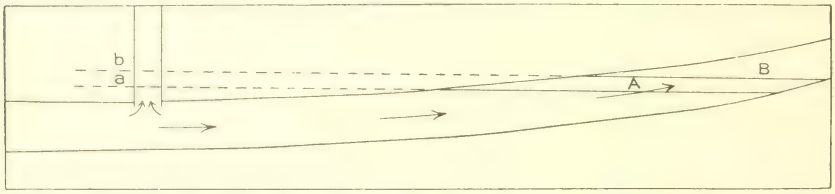


FIGURE 9.—Supposed conditions producing discoloration of waters in nonflowing wells. A, Normal water level in bed; a, normal water level in well; B, level in water bed during low barometer; b, level in well during low barometer.

probable that they are due to the same general cause. The disturbance in the well is probably not caused by the slight rise of the water in the well (a to b, fig. 9), but rather by a general movement of the whole water body (A to B), due to relief of pressure on the water surface, the silts or precipitates throughout the whole mass being disturbed. In this connection it may be said that most of the wells exhibiting this phenomena are shallow, so that direct barometric action on the water is possible.

REMEDIES.

SIMPLE TREATMENT.

Several simple methods of preventing wells from freezing are in common use, but owing to a failure to understand fully the causes of the freezing many of these methods fail and others are only partly successful. Some persons have the idea that freezing is caused by the chilling of the air inside the well by the transmission of the cold outside air through the casing, to remedy which the pumps are carefully wrapped in cloth, packed with straw, or otherwise protected. As a rule, this protection is entirely without effect, for the freezing does not occur in the manner assumed, but by access of air to the pipe at considerable depths. Other persons partly recognize the true cause of freezing and make an attempt to prevent access of air by packing earth, straw, or other material about the well. This practice is partly successful, as it tends to check the indraft of air, but the materials used are as a rule so porous that more or less air gets through them and the well freezes. The use of manure is somewhat more effective, for it warms the air that passes through it, but it involves great danger of pollution.

EFFECTIVE TREATMENT.

Freezing is due to faults in the construction of the well itself and can ordinarily be prevented only by remedying the defects of construction.

Open wells.—The air obtains access to open wells through the soil at the junction of curb and cover and through cracks in the curb or in the cover. As the soil is usually frozen in winter, little air enters the well in this way. The junction of curb and cover is tight in but few wells, and the cover itself, if of wood, is tight in none. The remedy for freezing consists in substituting cement for wood and in tightly fitting it to the curb, which should also be coated with cement for some distance below the surface.

Cased wells with escape at bottom.—The conditions in a cased well with escape at bottom are represented in figure 10, in which A is the outer casing; B, the inner or pump tube; C, the pump cylinder; and D, the well point. When the barometer is high the air is sucked in at E, at the mouth of the well, and passes off into the unsaturated sand at F. If the well is not pumped, it will not freeze at first, as the pipe contains no water above the water level G. If the well is pumped and the water is raised to the cylinder C and up pipe B, the cold air passing between A and B is likely to freeze the well. Even if the well is not pumped, the air current, if long continued, will eventually freeze the ground water at G and possibly also the water in the pipe.

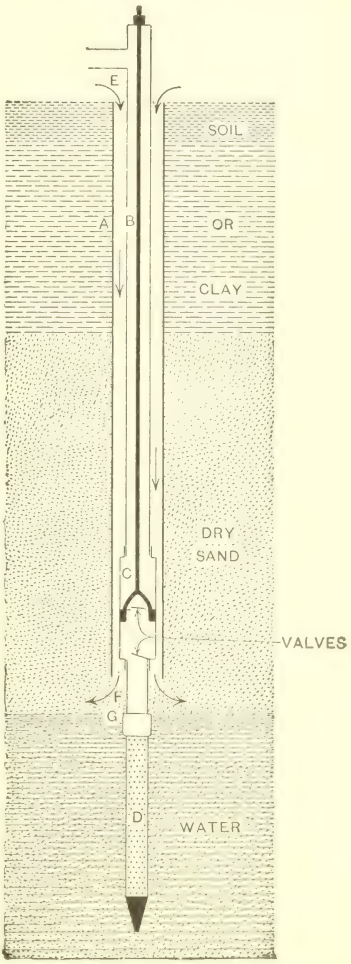


FIGURE 10.—Conditions governing freezing in cased well with escape of air at bottom. (Sanford.)

The remedy for freezing in such a well is to fill tightly the space between A and B at a point near the surface with some impervious material. A filling of cement resting on an improvised plug will probably effectively prevent freezing. The homemade rag packing sometimes used is generally too porous, permitting enough air to get through to produce freezing. Rubber plugs are effective, but care

should be taken not to use materials which can damage the water if they happen to drop to the bottom of the well. Manure should never be used about a well cased in the manner shown in the figure, as it can get to the water just as well as the air can.

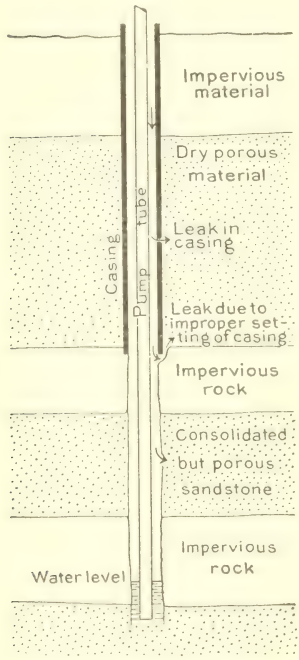


FIGURE 11.—Conditions governing freezing in wells with leaky casings and porous walls.

Wells with leaky casings.—Figure 11 shows a well which, though cased to a certain depth, has developed leaks by corrosion or imperfect joints and by careless setting of the casing in the rock. During periods of high barometer cold air enters the mouth of the well, passes downward between the casing and pump tube, and out into the porous stratum. The constant indraft of cold air quickly freezes the water remaining in the pipe after pumping.

The proper treatment is to plug effectually the space between the two pipes at a point near the surface.

Wells in porous rock.—The conditions in a well passing through porous rock are also illustrated in figure 11, in which the bed of sandstone, although stiff enough to stand without casing, may be sufficiently porous to permit large amounts of chilled air to enter from the well during periods of high barometer, resulting in freezing, as before. The remedy is a tight packing between the two pipes at a point near the surface.

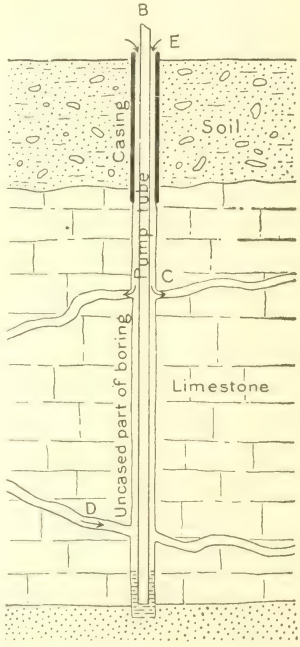


FIGURE 12.—Conditions governing the pumping in limestone wells.

Wells encountering open passages.—Wells encountering open passages are practically limited to limestone in which solution channels have been formed by circulating waters and later abandoned. In figure 12, which shows such a well, B is the pump tube and C an open passage into which air entering at the mouth of the well during periods of high pressure is carried off into the rock, producing a circulation which soon freezes water standing in the inner pipe. The treatment is the same as

that required for the well just described; it consists of plugging the well at E.

In many wells, however, this treatment is ineffectual, indicating that the cold air is not entering at E, but is circulating through underground passages, as indicated by the arrow at D. In such wells it becomes necessary to set the plug at the point where the passage is encountered, in this case at D. In some wells, as in one near Wabasha, Minn., the crevices through which the air is circulating are so numerous that the space between the outer and inner tubes must be filled from bottom to top with cement.

OCCURRENCE AND COMPOSITION OF WELL WATERS IN THE SLATES OF MAINE.

By Frederick G. Clapp.

INTRODUCTION.

There is a popular belief that little water can be found in slate. This idea is based on the very fine grain and impervious nature of the rock and on the fact that in regions where the strata are nearly horizontal slate acts as a confining stratum to hold water in more porous beds. Investigations of the underground waters of Maine in 1906 have shown, however, that in that State the slates contain more water than any other kind of rock, and that where they do not contain lime in detrimental quantities their water is the best found in the State.

CHARACTER OF MAINE SLATES.

The slates found in southern Maine are exceedingly diverse in character. Most commonly they are typical fine-grained, hard, black rocks, consisting of hardened clay, but in places they are schistose and even grade into true schist. In northeastern Maine and at a few places elsewhere in the State they are calcareous. Practically all the slates in the State are highly folded, and the stratification and cleavage planes dip at high angles. Near the coast the strike is diverse, but in many parts of central Maine it is very constant, being about N. 60° E. over broad areas. The dip is not so uniform, but is nearly everywhere high. The slates range from very hard to very soft.

WELLS IN SLATE.

NUMBER.

In the investigations all records of wells in Maine more than 50 feet deep were compiled, so far as they could be obtained. Nearly 600 such wells were found south of the forty-fifth parallel of latitude. For 385 of these it was possible to determine with certainty the type of rock penetrated. Of this number 214 were in slate and 37 in schist. As schist is in most places a metamorphic form of slate it is considered here with the slate. Thus, in southern Maine, 251

wells, or 70 per cent of those of which the type of rock is known, are in slate or schist. In northern Maine practically all the drilled wells are in slate or similar rocks; many of the rocks in this region are spoken of as "slated limestones," but they are in reality moderately calcareous slates.

PROPORTION OF SUCCESSFUL WELLS.

The following table includes all Maine wells more than 50 feet in depth in which the character of the rock could be determined:

Proportion of successful wells in various rocks in Maine.

Type of rock.	Successful wells.	Unsuccessful wells.	Total.	Percentage successful.
Schist	34	3	37	92
Slate	191	[a]23	214	88
Complex	42	[b]6	48	87
Granite	51	8	59	86
Gneiss	12	2	14	86
Trap and greenstone	10	3	13	77
	340	45	385	88

[a] Includes six wells ruined by entrance of ocean water.
[b] Includes one well ruined by entrance of ocean water.

From the table it will be seen that the proportion of successful wells (wells from which enough water for the domestic use of a moderate-sized family can be obtained) ranges in various rocks from 92 to 77 per cent. The table does not include gravel wells, which nearly always get a supply, but in which the character of water is uncertain. The table shows that in slate and schist the chances of obtaining water are somewhat greater than they are in any other type of solid rock in Maine. There is, however, a surprising uniformity in the proportion of successful wells in various rocks. It is also surprising to note that schist appears to offer better chances than slate, having 92 per cent of successful wells, whereas slate has only 88 per cent. With the 23 unsuccessful wells in slate, however, are included six wells which were ruined by the entrance of salt water, for the reason that they were drilled within a few feet of the ocean. These wells would undoubtedly have been successful if drilled a few hundred feet inland, and if the figures in the table should be changed so as to include these six wells with the successful ones, the percentage of successful wells in slate would be brought up to 91, corresponding closely with the proportion of successful wells in schist, with which no salt-water wells were included.

The table does not include any wells north of the forty-fifth parallel of latitude, as that region was not included in the investigation.

It is believed, however, from a hasty reconnaissance of the conditions in northern Maine, that practically all wells drilled in slate in that region are moderately successful.

WATER SUPPLY AND DEPTH.

In most rocks there is a more or less definite relation between the success of a well and its depth. In granite, for instance, there is a marked decrease in the amount of water found below about 200 feet. In order to learn whether any similar relation exists in slate the following table was compiled, taking into account all drilled wells more than 50 feet deep in which the rock is known definitely to be slate.

Data of slate wells in Maine.

Depth (feet).	Number yielding, in gallons per minute—					Successful; yield not known.	Too little water (failures).	Water not usable.	Total wells.	Per cent successful.
	1 to 5.	6 to 10.	11 to 50.	50 to 100.	Over 100.					
50–100	30	7	11	1	.....	63	5	6	123	91
100–200	9	3	14	.....	.....	15	7	2	58	85
200–300	3	3	9	2	1	12	1	1	32	94
300–400	1	1	.....	2	.....	.....	.....	1	5	80
400–500	.....	.....	2	.....	.....	.....	.....	.....	2	100
More than 500	.....	.....	1	.....	.....	.....	1	.....	2	50
	43	14	37	5	1	90	14	10	214	88

The most important column in this table is the last, which shows the percentage of successful wells of various depths. The unsuccessful wells include both those in which too little water was obtained for the use of a family of ordinary size, and those in which the water was so poor as not to be usable. Of the ten poor wells, six were ruined by the incursion of salt water.

The proportion of successful wells in granite and other crystalline rocks decreases from about 95 per cent for wells less than 100 feet deep to a low figure for the deeper wells. In slate, however, there is no such regular decrease with increase in depth. Of the 123 wells between 50 and 100 feet deep 91 per cent were found to be successful; of the 58 wells between 100 and 200 feet deep 85 per cent were successful; and of the 32 wells between 200 and 300 feet deep 94 per cent were successful. The wells deeper than 300 feet are few and the figures for them carry little weight. Evidently, however, there is no close relation between success and depth of well. The greatest success was obtained with wells between 200 and 300 feet deep.

The facts above stated were unexpected by the investigator, for it had been supposed that, as in granite and crystalline rocks in this and other States, little water would be found in slate below 200 feet. The difference is probably due to the difference in the character of the rock. In granite and most crystalline rocks the water occurs entirely in joint

cracks, which tend to close with increase in depth and are few in number below 200 feet, but in slate the water occurs not only in the joint cracks but also in minute crevices along the stratification and cleavage planes, and in calcareous slates it may occur in cavities formed by solution. The stratification and cleavage planes, like the joint cracks, probably close with increasing depth, but as they do not correspond in direction with the joint cracks the pressure of the rock in any particular direction would close only a part of the cavities which might hold water. It can not be said definitely what proportion of the Maine slates are calcareous enough to contain dissolved cavities, but it is known that in some places thin layers of limestone are interstratified with the slate, and it is probable that in such places the water occurs in cavities.

The chief lesson to be learned from the above table is that in drilling in the Maine slates the chances of obtaining a sufficient and suitable water supply at less than 200 feet from the surface are about 90 in a hundred. If such a supply is not found, however, it is worth while to continue the drilling to at least 300 feet. If the yield is still insufficient, it might even pay to drill 100 or 200 feet deeper. In all rocks, however, great pressure exists below the surface, and it is probable that the crevices are closed below the depth of a few hundred feet. The statements made here do not apply to any kind of rock except the slate of compact type and possibly to schist.

PRINCIPAL WATER VEIN.

The foregoing statements as to depth of well do not mean that the principal vein of water in the wells is always found at the maximum depth. In only 123 out of the 214 wells drilled in slate could the depth to the principal water vein be ascertained. The relation of the depth of this vein to the depth of the well, so far as known, is given in the following table:

Relation of principal water vein to depth of well.

Depth of well (feet).	Number of wells in which depth to principal water vein (in feet) was—						
	0–50.	50–100.	100–200.	200–300.	300–400.	400+.	Total.
50–100	27	45					72
100–200	3	8	12				23
200–300	3	3	7	8			21
300–400	1	1		1	1		4
More than 400					1	2	3
	34	57	19	9	2	2	123

The most interesting feature brought out by the foregoing table is that the depth of the principal water supply generally bears little relation to the depth of the well. Usually in slate wells there is no

one crack which yields all the water, but many cracks which furnish water, so that with continued drilling the supply becomes sufficient. In most wells one opening yields more water than the others, and this is called the "principal water vain." A comparison of the figures shows that in slate the supply is not necessarily to be expected within 50 feet of the surface, although it is frequently found at shallow depths. The figures corroborate those in the first table, showing that wells may be drilled to 200 feet, or even to more than 300 feet, with a fair expectation of increased yield.

FLOWING WELLS.

In general, flowing wells are not looked for in slate. In Maine, however, there are 24 flowing wells in slate, out of 39 recorded in all kinds of rock. Ten of the flowing slate wells are in Cumberland County, 5 are in Piscataquis County, and the remainder are scattering. The best flowing wells in the State are those at Greenville, in Piscataquis County, where the water rises 10 to 20 feet above the surface. All the flowing wells are believed to be due to the arrangement of joint cracks in the rock by which the water penetrates downward beneath an impervious surface coating of bowlder clay and reaches the surface when tapped by wells at suitable points in the valleys.

COMPOSITION OF SLATE WATERS.

It is not supposed that the quality of slate waters of Maine is characteristic of all waters occurring in slate in other regions. There is, however, a considerable degree of probability that the average quality of water found in this rock in Maine is fairly typical of the quality of that from the metamorphic slates which are so widely distributed throughout the country.

In the investigation of the underground waters of Maine over 100 analyses of slate waters were collected and compiled. Of these about 25 were detailed chemical analyses made by Prof. F. C. Robinson, of Brunswick, Me. These record the character of the water with considerable accuracy and are probably the most reliable analyses of slate waters known. In order to give a good idea of the character of these waters, the following table is appended, giving 13 characteristic analyses of waters widely scattered throughout the State:

Composition of waters from wells drilled in slate in Maine

[F. C. Robinson, analyst. Quantities in parts per million.]

No.	County.	Locality.	Owner.	Depth (feet).	Total solids.	Organic and volatile matter.	Silica (SiO_2).	Iron and aluminum oxides (Fe_2O_3+ Al_2O_3).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Sulphate radicle (SO_4).	Chlorine (Cl).
1	York	Kittery	Roland Thaxter	75	208.7	14.6	11.0	3.2	46.8	12.8	26.6	8.7	14.1	40.
2	Cumberland	Cape Cottage	Amos Miller	115	140.0	22.5	9.0	.9	43.0	2.4	10.8	3.8	15.1	18.5
3	....do	Mere Point	W. D. Pennell	67	88.2	29.9	8.8	2.0	7.0	4.5	7.3	1.5	22.4	10.4
4	Kennebec	Winthrop	C. M. Bailey Sons & Co	307½	226.9	20.3	15.5	2.0	56.7	6.3	26.6	5.0	62.9	7.5
5	Waldo	Belmont	Horace Chenery	187	138.2	9.5	16.8	2.5	23.1	6.4	15.2	6.1	13.6	5.0
6	....do	Searsport	W. E. Grinnell	100	162.4	10.6	21.0	3.0	28.4	5.1	21.2	6.2	27.5	22.0
7	Hancock	Bucksport	Eastern Maine Conference Seminary	308	115.7	9.6	15.1	1.8	25.5	3.6	17.7	2.2	22.3	6.5
8	....do	Hancock	Jeremiah Stratton	65	108.8	10.5	14.8	1.0	14.7	2.9	6.7	2.3	10.9	11.9
9	Penobscot	Bangor	Maine Creamery Co	120	86.0	21.4	6.7	.7	20.1	5.7	4.0	.8	5.9	21.0
10	....do	....do	High School	217	180.0	37.1	10.2	1.1	46.0	7.4	11.7	1.3	18.2	50.0
11	Piscataquis	Greenville	H. M. Shaw Manufacturing Co	155	52.1	7.7	13.8	.4	10.0	3.6	2.0	.5	6.8	2.5
12	Aroostook	Houlton	Houlton Grange	75	354.7	33.0	16.1	4.3	77.6	36.0	16.5	.5	16.0	51.2
13	....do	Van Buren	D. Murray	105	755.9	146.8	20.8	.8	159.2	12.1	21.0	39.0	30.5	129.6
	Average				201.3	21.0	13.8	1.8	42.9	8.4	14.4	6.0	20.5	28.9
	Average of 7 samples of granite waters				218.7	45.7	15.2	2.7	33.4	4.6	23.4	5.5	18.7	45.2

The table shows that the total solids found in slate waters in Maine range from 50 to 750 parts per million, the lowest proportion being in the hard metamorphic slates of western and southern Maine, and the highest, as a rule, in the calcareous slates of Aroostook County. The silica ranges from 6 to 21 parts per million, but does not seem to hold any definite relation to locality. Iron is nearly always absent, but the solids include some alumina, and the figures for iron and aluminum oxides range from 0.4 to 4.3 parts per million. The most variable constituent, with the exception of chlorine, is probably calcium, which ranges from 7 to 159 parts. As calcium is the principal constituent of lime, its amount is rather closely associated with the proportion of lime in the rocks, and the waters having the most lime are, as a rule, the hardest. The hardness is also dependent to a certain degree on magnesium, which ranges from 2.4 to 36 parts per million. Sodium ranges from 2 to 27 parts, potassium from 0.5 to 39, and chlorine from 2.5 to 130. The average composition of the slate waters of Maine, as calculated from these analyses, is given in the table. It will be seen that a slate water with an average composition would contain 201 parts per million of total solids and 43 parts per million of calcium, which would seem to be a rather soft water.

In order to compare the composition of slate water with that of granite, the average composition of granite waters as represented by seven analyses from different parts of the State is given at the foot of the table. It will be seen that while granite contains on an average more soluble mineral matter than slate does, the amounts of calcium, magnesium, and sulphates in slate are considerably higher than they are in granite. Hence slate waters, if the above analyses can be taken as representative, may be said to be, as a rule, somewhat harder than granite waters, though some slate waters which do not contain the sulphates and carbonates of calcium and magnesium are very soft. No tests for hardness were made in any of these analyses.

COST OF DRILLING.

The cost of drilling in slate is not so great as in granite and other crystalline rocks, and there is little reason why drilled wells in slate should not be preferred to dug wells. In Aroostook County, where the rocks consist of rather soft slate, the cost is only about $1 a foot, the well being cased to rock and the casing being furnished by the drillers. In Penobscot County the charge is generally about $3 a foot for the first 50 feet, $4 for the second 50 feet, and $5 for every foot below 100. In the more wealthy of the summer-resort regions drillers are likely to charge more, and on the islands a higher charge is necessary owing to the additional expense of getting machines and

fuel across the water. The speed of drilling varies according to the hardness of the slates. Generally 2 to 10 feet a day can be accomplished, but one well is reported to have been sunk 35 feet in a single night.

SUMMARY.

Plenty of water of excellent quality can be found in most of the types of metamorphic slate that occur in Maine. This water may be found almost anywhere within the first 500 feet below the surface. The largest supplies are found generally between 200 and 300 feet, but abundant water for a family of ordinary size is usually to be had within 100 feet from the surface. The deeper wells are recommended wherever they are practicable, as they are safer from pollution. The cost of drilling wells in slate is less than in any other kind of rock in Maine, and a drilled well will always be cheapest in the end. The composition of slate water is uncertain, but the water is always excellent for drinking, and, except in a few regions where there is considerable lime in the rock, it is not too hard for boilers and causes very little scale.

OCCURRENCE AND COMPOSITION OF WELL WATERS IN THE GRANITES OF NEW ENGLAND.

By Frederick G. Clapp.

INTRODUCTION.

From time immemorial it has been commonly believed that an available supply of water does not exist in granite. This belief, though erroneous, appears to be well founded when it is considered that granite is one of the hardest rocks and that where it is exposed at the surface it is usually very solid and free from pores or crevices in which water might be held.

Until within the last few years few wells had been drilled in crystalline rocks. The conditions of the occurrence of water in such rocks have thus been little understood, and it has not been generally recognized that in many places they are traversed by numerous cracks along which water penetrates and in which it is held.

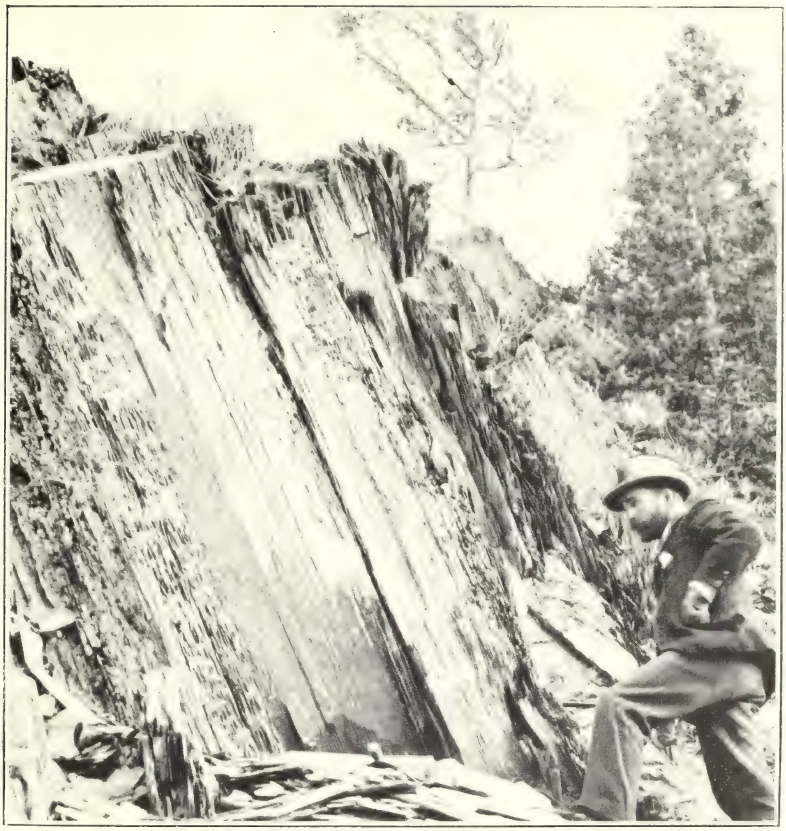
The literature bearing on this subject is scanty, but Ellis[a] has described the conditions under which water exists in crystalline rocks in Connecticut, as found during an extensive investigation of the underground waters of that State. The information obtained was of great practical value, as it showed that plenty of water exists in these rocks, although its presence or absence at any particular spot can not be predicted. Of two wells that are drilled side by side, one may be a failure and the other a success.

Field work by the writer in eastern Massachusetts and southern Maine in 1906 furnished considerable additional information regarding deep-well waters obtained in granite, a rock which covers large areas in these States.

CHARACTER OF MAINE GRANITES.

Granite varies in character. The most common variety consists of a moderately coarse-grained, light-colored crystalline rock, composed of quartz, feldspar, and mica or hornblende. Granite ranges

[a] Ellis, E. E., Occurrence of water in crystalline rocks: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, pp. 19–28.



A. WATER IN SHEET JOINTS IN GRANITE.

(See p. 41.)

B. SINK HOLES CONNECTED WITH UNDERGROUND DRAINAGE.

(See p. 49.)

in texture from a rock so fine that the grains are barely perceptible to a coarsely crystalline graphic granite (pegmatite), composed of crystals measuring several inches across. The rock commonly quarried as "black granite" is really a diorite. Many varieties of granite are found in Maine, but the one which covers the largest areas and in which most of the wells sunk in granite have been drilled is of moderately coarse texture. In many places it grades into the banded variety known as gneiss, and as the conditions that allow the penetration of water in gneiss are similar to those in granite, gneiss is included in the following discussion.

OCCURRENCE OF WATER IN GRANITE.

All rocks are traversed by numerous fissures or joint cracks, and these openings contain practically all the water that is found in granite. Most of the fissures are arranged in systems having a fairly constant trend, but there are also many that do not belong to any regular system. Some fissures are approximately vertical and extend many hundred feet in one direction, and along them water may find its way downward from the surface.

The vertical joints, though not at all regularly placed, are commonly 10 to 20 feet apart. They trend in all directions, but in most regions the greater number fall into a series which has a fairly constant direction or strike. These joints stand vertically or at steep angles ranging up to 30° from the vertical. There are also abundant cracks approximately parallel with the surface, as horizontal or sheet joints. These range from a few inches apart near the surface to many feet apart at a depth of several hundred feet. In a well at Stonington, Me., 27 distinct fissures from a few inches to 14 feet apart were passed in sinking to a depth of 94 feet.

Water may be held in sheet joints until it is tapped by a well, or it may find its way downward toward some adjacent lower ground. The occurrence of water in joint cracks is shown in Plate I, *A*, which illustrates a granite quarry at North Sullivan, Me. The more nearly vertical joints serve as channels for admitting the water from overlying surface deposits, and the sheet joints form reservoirs in which it is stored.

As most of the joints in granite are mere seams, the amount of water contained in them is necessarily small. Occasionally as much as 30 gallons a minute has been obtained with a steam pump, but in most wells the amount yielded is not over 10 gallons a minute.

On account of the great irregularity of the spacing of joints in granite, the success of any well in this kind of rock is wholly a matter of chance, dependent on whether the location is a fortunate one with

respect to the arrangement of the joints. Figure 13 shows how a well may be sunk several hundred feet without striking a single joint crack, and in such a well no water will be found. More often many joint cracks are cut by the well. Where they are numerous an increased amount of water may be found by deeper drilling, but instances have been known where continued drilling struck an open

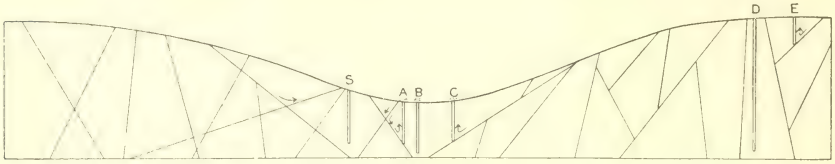


FIGURE 13.—Conditions of wells in jointed granite. A and C, Conditions under which flowing wells may be obtained; B, D, and S, conditions under which no water may be found; E, normal condition of obtaining water in drilled wells; A, conditions under which well may be polluted by drainage entering joint cracks near mouth of well.

crack in which the water was lost. Such uncertainty of results is one of the characteristics of well drilling in granite and similar rocks. Of two wells drilled within 50 feet of each other one may be a failure and the other a marked success, the result depending on whether or not a water-bearing fissure is struck.

PROPORTION OF SUCCESSFUL WELLS.

An effort has been made to obtain accurate information regarding the proportion of wells drilled in granite which are successful. Such an estimate is difficult to make for several reasons. Most well drillers are inclined to be optimistic and report few if any failures; failures are also apt to be forgotten by residents of a community; engineers, well drillers, and well owners do not agree as to what really constitutes a sucessful well; finally, a well that may properly be called successful where but a small water supply is needed is a failure if a large amount is required. The United States Government has abandoned wells in the East because the supply was only 10 to 20 gallons a minute, and in the irrigating communities in the arid States wells that yield even 200 or 300 gallons a minute may be called failures because 400 or 500 gallons is required to make the enterprise successful. For ordinary domestic purposes in the Eastern States 1 or 2 gallons a minute will usually suffice for a single family, but if less water than this is obtained the well is generally ranked as a failure.

A few experienced drillers report one or two wells out of a hundred that do not yield sufficient water. Sometimes there is a disagreement between the driller and the owner, owing to the fact that the well produced a fair amount of water when the vein was first struck by the drill, but later the water gave out. For this reason some of the more experienced and reliable drillers will not leave a well until

a sufficient time has elapsed to determine whether or not the supply will be permanent.

It is difficult to decide what really constitutes a successful well. In the following table a successful well is considered as one which supplies enough water for ordinary domestic use, generally about a gallon a minute. In compiling the table all wells more than 50 feet deep in which the rock was known to be granite were considered, but it has been necessary to omit a few wells whose yield is not known. These are mainly wells that have been long abandoned, owing to installation of public supplies or to other causes. The unsuccessful wells include both those in which little water was found and those in which it was of inferior quality. All known instances of inferior quality of water from wells sunk in granite are due to the influx of sea water.

Relative success of wells sunk to different depths in granite.

	Number of wells with depth of					Total wells.
	50–100 feet.	100–200 feet.	200–300 feet.	300–400 feet.	Over 400 feet.	
Yield (gallons per minute):						
1 to 5	7	5	2	2		16
6 to 10	5	1				6
11 to 50	6	7	5			18
Over 50	1	1	1			3
Successful; yield not known	19	6	3		1	29
Too little water	2	2	3		1	8
Water not usable			1	1		2
Total wells	40	22	15	3	2	82
Per cent successful	95	91	73	67	50	87

By a study of the table it will be seen that 87 per cent of the wells drilled in granite of which records are available were successful enough for ordinary domestic use. The other 13 per cent were wells in which water was absent or insufficient in quantity, or in which it was not usable because the wells were drilled near the ocean and salt water entered them along the open joint cracks. Of 72 successful wells only 3 were reported to produce over 50 gallons of water a minute.

WATER SUPPLY AND DEPTH.

There seems to be a general belief that where water occurs it increases in quantity with the depth of the well, and some people suppose that water may be found anywhere if a well is only drilled deep enough. This belief, however, is incorrect. Although water can usually be found by drilling in granite, it may not exist at a depth of several hundred feet. The joint cracks and other fissures in the rocks close at a great depth, owing to the pressure, and hence they can hold no water.

In the investigation of underground waters in crystalline rocks in Connecticut, previously referred to, Ellis found that below a depth of 200 feet the chances of obtaining water greatly decrease. The same conclusion has been reached in a study of the granites of Maine, but it is not found to be true of all rocks. One of the most experienced well drillers in Maine informed the writer that the maximum depth to which it is advisable to drill in granite is 185 feet, below which the chances of striking a supply of water decrease. This estimate was based on the results of all the wells sunk by him and agrees with the facts indicated by the foregoing table. By far the greater portion of wells drilled in granite to a depth of more than 50 feet do not exceed 100 feet. About half of those deeper than 100 feet do not exceed 200 feet, and only two granite wells are known to be more than 400 feet deep. The most important figures in the table are those showing the percentage of successful wells. To summarize these figures it may be stated that the chances of obtaining a good water supply by drilling in granite range from 95 per cent for wells less than 100 feet deep to only 50 per cent for wells more than 400 feet deep. Below 200 feet the chances of success decrease very rapidly, and those who drill below this depth take the risk of incurring more expense than would be involved if they should stop drilling and sink another well 50 or 100 feet distant.

The same conclusion is reached by a study of the following table, which shows the relation of the principal water vein to the depth of the well. From the totals it will be seen that of 47 wells in granite, which record the depth to the principal water supply, in 17, or over one-third, it is found within 50 feet of the surface; 16 more, or over half the remainder, reach it within 100 feet of the surface; 7, or half the recorded wells over 100 feet deep, obtain their principal supply from depths of 100 to 150 feet; 3 more get it between 150 and 200 feet; and 4 wells, or half of the wells more than 200 feet deep of which records are available, get their most important water vein below 200 feet.

Relation of depth of principal water vein to depth of well.

Depth of well (feet).	Number of wells in which depth to principal water vein (in feet) is—					
	0–50.	50–100.	100–150.	150–200.	200–250.	Total.
50–100	13	13				26
100–150	2	1	5			8
150–200	1		2	2		5
200–250	1	2			3	6
250–300					1	1
Over 300				1		1
	17	16	7	3	4	47

COMPOSITION OF GRANITE WATERS.

In the investigation of the underground waters of Maine, over sixty 1-gallon samples were collected from wells in different parts of the State and were analyzed by Prof. F. C. Robinson, of Bowdoin College. Nine of these samples were collected from wells drilled in granite in Hancock, Lincoln, and Cumberland counties.

With two exceptions the amount of total solids in the samples ranges from 81 to 419 parts per million. The exceptional waters are those of a well at the glue factory at Vinalhaven, and of a well belonging to C. A. Sproul at Pemaquid Beach. As both these wells are near the sea and as their waters are high in minerals in the proportions which would be expected where well water was mixed with ocean water, there is believed to be such a mixture in these wells and they were discarded in compiling the subjoined table. The seven remaining analyses are given in the order of the depth of the wells, which ranges from 25 to 279 feet. Comparison of the constituents shows no relation between the depth of the well and the proportions of any of them.

The average composition of granite water, as given in the table, is the average calculated from the seven analyses. With several of the constituents this average is considerably higher than the most common composition, for the reason that one or two exceptionally high figures raise the average. Granite water, when not contaminated by surface drainage, is excellent for drinking and is probably satisfactory for every ordinary use. A comparison of the average composition of granite waters with the average composition of slate waters calculated from 13 analyses shows that the former contain a somewhat higher amount of total solids. Slate waters are, however, the harder, as shown by the greater amount of calcium and magnesium, which are probably present mainly as carbonates and sulphates. No tests for hardness were made in these analyses.

Composition of granite waters from drilled wells in Maine.

[F. C. Robinson, analyst. Quantities in parts per million.]

No.	County.	Locality.	Owner.	Depth (feet).	Total solids.	Organic and volatile matter.	Silica (SiO_2).	Iron and aluminum oxides (Fe_2O_3+ Al_2O_3).	Calcium (Ca).	Magnesium (M_3).	Sodium (Na).	Potassium (K).	Sulphate radicle (So_4).	Chlorine (Cl).
1	Hancock	North Sullivan	J. M. Blaisdell	25	195.7	26.9	8.3	4.7	37.4	4.3	25.6	5.6	14.9	41.2
2	do	do	Crabtree & Havey	51	364.3	66.7	12.5	2.1	62.4	3.4	61.8	3.7	16.0	140.0
3	Lincoln	Waldoboro	Miss E. F. Genthner	56	418.9	99.5	10.9	3.5	56.6	9.0	29.5	13.0	36.0	56.6
4	do	Damariscotta Mills	G. W. Waltz	64	129.0	29.0	23.8	2.5	18.1	2.9	13.1	5.8	13.6	15.0
5	Hancock	Greeninge Island	J. G. Thorp	88	81.4	5.2	8.5	1.1	1.1	1.8	11.0	1.7	14.7	23.1
6	Cumberland	Bridgton	J. K. Martin	125	205.5	74.0	31.1	2.8	28.9	7.6	9.6	6.9	9.5	23.5
7	Hancock	Stonington	J. C. Rogers	279	136.5	18.6	11.2	2.0	29.3	3.4	13.0	1.9	25.9	16.9
	Average composition				218.7	45.7	15.2	2.7	33.1	4.6	23.4	5.5	18.7	45.2
	Average composition of 13 samples of water from slate				201.3	21.0	13.8	1.8	42.9	8.4	14.1	6.0	20.5	28.9

COST OF WELLS IN GRANITE.

As granites and gneisses are among the hardest rocks known, drilling in them is difficult and expensive. Generally the well is not deepened more than 3 to 5 feet a day and sometimes only a few inches. The cost is necessarily an important factor in the sinking of wells. It not only varies with the kind of rock, but with locality and other conditions. The price for drilling 6-inch holes in granite on the coast of Maine ranges from $4 to $6 a foot, the higher figure being the more common. Most drillers charge about $1 a foot more for drilling on the islands than they do on the mainland.

A significant fact is brought out by comparison of the cost of drilling granite wells and the cost of blasting open wells in granite. In some parts of Maine $6 a foot is the rate charged for either of these methods. A blasted well is necessarily limited to a few feet in depth and is open to the chance of pollution through surface drainage, which may easily enter it. Both these objections are less applicable to a drilled well, which is therefore to be preferred as a permanent investment.

SUMMARY.

To summarize, it is safe to say that under the conditions which prevail in the New England States about 90 per cent of the wells drilled in granite will find enough water to supply the domestic needs of a family. In about 85 per cent enough water will be found within 100 feet of the surface. A well should not be abandoned without sinking at least 200 feet, but drilling deeper than 200 feet is not advisable, although a few wells have procured water at greater depths. If a well owner does not obtain sufficient water at 200 feet, he is advised to sink a second well 100 feet or more distant, and the chances are good that the second attempt will be successful.

Although granite water is moderately charged with mineral matter, it is not hard and is known not to contain sufficient mineral matter to interfere with its use.

POLLUTION OF UNDERGROUND WATERS IN LIMESTONE.

By George C. Matson.

INTRODUCTION.

With increase in density of population the maintenance of the purity of water becomes a matter of vital importance. In a few places it is possible to procure supplies which have moved long distances through beds of sand capped by clay or other impervious materials. Such supplies are essentially free from pollution because whatever polluting matter they may have contained has been removed by the natural filtration they have received in their passage through the sand. Unfortunately, however, in many localities it becomes necessary to use supplies which receive little or no natural filtration. In such places it is necessary either to prevent pollution or to resort to some method of artificial purification. Even the most ardent advocates of filtration will admit that the purification of polluted water must always be more or less imperfect. For this reason it becomes desirable to prevent pollution, and this can be accomplished only when the source of the polluting matter and the methods by which it reaches the water are thoroughly understood.

In limestone regions where the country rock is covered by a thin mantle of residual materials the dangers of pollution are very great, and there is practically no opportunity for natural purification. The danger is enhanced by the fact that persons using underground water are apt to rely on its appearance and temperature as indications of purity. It is generally considered that water which is clear and cold is pure, but no such conclusion is warranted, for some of the most dangerously polluted waters are free from sediment and as cool as ordinary well or spring water.

OCCURRENCE OF WATER IN LIMESTONE.

Pores.—In order to understand the manner of pollution in limestone it is necessary to review briefly the mode of occurrence of underground water in such rocks. A few limestones are sufficiently porous to absorb much moisture, but most of them, especially those in the

older geologic formations, are too dense to absorb water. In this paper the porous limestones will not be considered, the discussion being confined to those limestones which yield water from more or less open passages.

Joints.—Limestones are usually traversed by at least two sets of vertical joints, making approximately right angles with each other. Other partings at right angles to these joints form the bedding planes of the rock. The spacing of joints is fairly uniform over considerable areas, and the interval is commonly to be measured in feet, though where the rocks have been deformed the number of joints is increased. The bedding planes usually show little uniformity of arrangement, and an interval of a few inches may be followed by one of much greater magnitude.

Caverns.—The water which comes from limestones usually makes its way along enlarged joints known as caverns. The enlargement is due to solution of the limestone by water containing carbonic acid. Obviously the places where water circulates most readily will, other things being equal, suffer the greatest loss by solution, but differences in the solubility of the rock may offset the effect of rapid circulation.

Doubtless the most common locality of rapid solution is at the intersection of a prominent bedding plane and a more or less open joint. Owing to the presence of numerous open joints or to the solubility of the rock, very large chambers, called domes, are formed in certain places where a considerable amount of water enters the underground channel. This water, coming fresh from the surface, is armed with a great amount of carbonic acid and attacks the limestone about the point of entrance. As it flows farther and farther from this point it loses its power to dissolve, because it has gradually picked up as large an amount of calcium carbonate as it can carry.

The belt of rapid solution is limited to the zone of active water circulation, and the formation of caverns therefore takes place largely above the level of the surface streams which receive the underground drainage, but this does not imply that there is no deep-seated solution nor that active circulation may not in some places extend slightly below the level of surface drainage.

Sink holes.—As solution progresses some parts of the cavern roof become so weakened that they collapse, forming sink holes (Pl. I, *B*, p. 40). If the channel beneath the point of collapse is large in proportion to the amount of material which falls, the sink is an open hole; but if the amount of fallen material is sufficient to clog the channel, the sink appears as a rounded depression which has no outlet. The fallen material may obstruct the opening so that the stream appears at the surface, or it may leave a passage which will allow

the drainage to continue underground. In this event the gradual wearing of the stream may remove enough of the fallen material to form an open sink.

UNDERGROUND STREAMS.

RELATION TO SURFACE DRAINAGE.

Downward migration.—In the process of deepening its valley a stream lowers the base level of its tributaries and thus affords them an opportunity to degrade their channels. When the tributaries flow in caverns they lower their channels along joint planes, and the process goes forward most rapidly along some particular lines, just as in the formation of the original cavern. At certain places where there is rapid downward movement from the old to the new channel more or less rounded openings are developed. These openings furnish a passage from the old to the new cavern and are usually called pits. They often form beneath the domes mentioned above, their

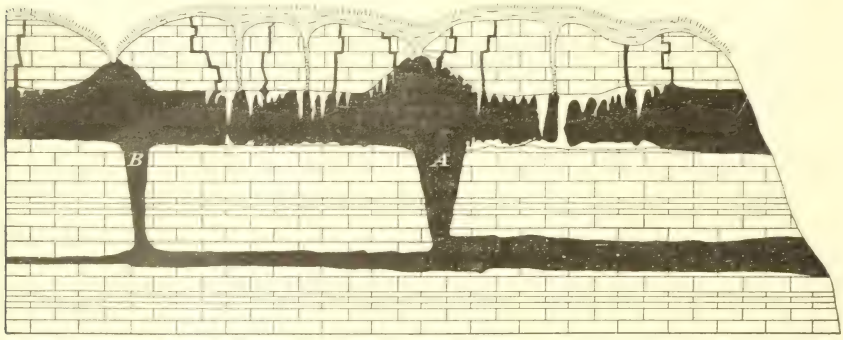


FIGURE 14.—Cavern showing different levels of underground streams.

location being determined in part by the presence of initial crevices and in part by the same condition which produced the domes, namely, the entrance of surface water bearing considerable free carbonic acid. (See *A*, *B*, fig. 14.) Doubtless the formation of both pits and domes is aided by the mechanical action of the water, especially where it contains sediment. As long as the lower channel or the passages leading to it are comparatively small the old cavern retains a large part of the drainage. With the enlargement of the new cavities the old channel receives less and less of the original drainage until it is entirely deprived of its original headwaters except during storms, and at last, when the new channels have become sufficiently enlarged, the old channel receives only the drainage of its local tributaries.

Migration from higher to lower levels may take place at successive intervals, leaving a series of abandoned channels at different levels. The course of the underground stream at each successive stage probably deviates more or less from the course of the abandoned channel.

Moreover, the course may not lie in a single channel, but passages may divide and subdivide, forming a more or less extensive network of channels.

Effect of shale beds.—If a shale bed is encountered by the water in its downward progress a cavern is usually formed above it, and if the shale bed is a considerable distance above the level of the surface stream which receives the drainage from the cavern the water may emerge from the cliff above the surface stream. The mechanical wear of the underground stream may remove the shale at some point and thus permit the formation of another channel nearer the level of the surface stream. If the shale bed is of considerable thickness the downward migration of water may be permanently obstructed. The lowering of the surface streams usually takes place much more rapidly than the lowering of the underground streams. In consequence of this fact the underground streams may remain considerably above the level of the surface stream, even where there are no beds of shale or other dense material to prevent downward migration.

Change from an underground to a surface stream.—The numerous points of weakness in the roof of an old cavern may result in the development of a line of sink holes, which serves to indicate the course of underground streams. As the work of undermining the roof progresses the coalescing of the sink holes may give an open channel for a considerable distance.

If this happens at the lower end of the underground stream a gully is formed with a large spring at its head. This explains the common occurrence of springs in such situations rather than along the valleys of the large surface streams. A segment of the roof of a cavern may fall and the water, after emerging as a spring and flowing for some distance as a surface stream, may reenter its underground channel through an open sink. Sinking streams are very common in limestone regions. Where all but a small section of the roof of the underground channel falls the section still left standing is known as a natural bridge.

TRACING UNDERGROUND STREAMS.

Because of the great complexity of the underground drainage the tracing of underground streams is a task requiring the exercise of considerable patience. If it is possible to enter the underground channels, a survey may be made; but most of these channels are inaccessible and some other method must be used. The common methods of tracing such streams may be grouped under two heads—chemical and physical.

Chemical tests are made by dissolving certain materials in water and introducing them into the underground stream either directly through open holes or by seepage through the soil. The compounds

most commonly used are chlorides of sodium, calcium, or ammonium, nitrate of potassium, and salts of aluminum or iron. After the introduction of one of these substances chemical tests are made at frequent intervals to detect its presence in samples taken from the well or spring that is supposed to receive water from the underground stream.

Physical tests are made either with coloring or suspended matter. The coloring materials commonly used are potassium permanganate, fuchsine, Congo red, methylene blue, and fluorescein. Suspended matter may be of either microscopic or megascopic size. Such substances as flour, starch, or cultures of bacteria may be introduced into the water of the underground stream and the suspected spring or well water examined to determine their presence or absence. For microscopic tests wood, sawdust, leaves, oil, and many other substances are used.

The choice of the material for tests will depend largely on the local conditions. Oil and other substances which float on the water are satisfactory only where there are no quiet reaches of water and no marked constrictions in the channel to delay their progress. In some experiments they have proved satisfactory; in others they have given negative results. They are useful in connection with chemical or with other physical tests because they give an idea of the character of the underground stream.

In one test oil, fragments of wood, and common salt (NaCl= sodium chloride) were used in a single underground stream. The materials were put into the stream through an open sink about one-eighth of a mile from its point of emergence in a spring. The oil appeared at the spring in one hour and the salt in seven hours; the wood fragments had not appeared after a lapse of several days. The writer has found salt very satisfactory for testing streams having a flow of several million gallons or less daily, but its use would be impracticable in very large streams such as are found in some caverns.

DEPOSITS IN CAVERNS.

After the abandonment of a section of the underground stream the amount of water entering the old channel becomes less and less until it is confined largely to small seeps. At this stage much of the water is removed by evaporation and the process of solution gives place to that of deposition. At first deposition is rapid because the crevices are large enough to supply all the water that can be evaporated, but gradually as the points of ingress become closed by deposition the amount of water entering diminishes until finally it may cease altogether, leaving a portion of the cavern dry. Although the greater part of the deposition in caverns takes place after the active work of solution has ceased, the two processes may go on at

the same time and there is always a gradual transition from one to the other.

The products of deposition are the stalactites, stalagmites, and various irregular masses which ornament caverns. These are always most numerous in the upper levels, though they may form to some extent in all the underground channels.

POLLUTION OF LIMESTONE WATERS.

CHARACTER.

Suspended matter.—Certain waters may be rejected as unfit for use because they contain straw or other materials of organic origin, and the wisdom of such rejection is too apparent to need comment. On the other hand, the presence of sediment in water is often taken as an indication of the entrance of surface water through an open sink; such a conclusion, however, may be wholly erroneous.

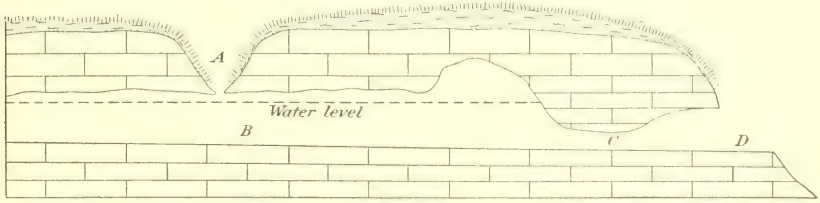


FIGURE 15.—Diagram of cavern showing how sediment may be deposited by the underground stream.

Figures 15 and 16 show that the presence or absence of sediment can not be considered a safe indication of the presence or absence of surface drainage. In the cavern shown in figure 15 sediment-laden surface water entering at *A* may be so retarded in the chamber *B* that it deposits its sediment and passes through a constricted channel, *C*, to emerge at *D* comparatively free from sediment.

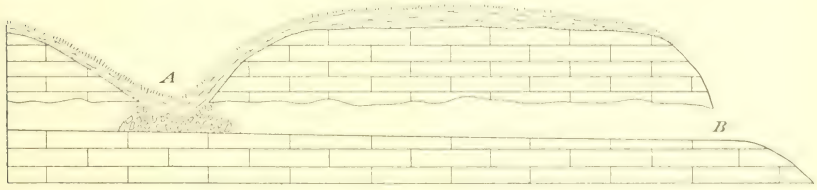


FIGURE 16.—Diagram of cavern showing how sediment may be obtained by the underground stream.

This water, though comparatively clear, may contain a large amount of surface drainage in some other form. In the cavern shown in figure 16 the water may obtain sediment at the closed sink *A* and emerge at *B* so turbid as to indicate a direct connection with surface drainage.

The conditions represented by these two figures are transitory, for in the cavern of figure 15 the chamber *B* will soon become partly filled with silt, so that the water passing through the channel *C* will transport a considerable amount of sediment, and in the cavern of figure 16 the gradual removal of material from the sink *A* will soon form an open hole. Sediment may also be deposited in caverns during low-water periods and then washed out during high-water periods. Solutions of organic matter may be temporarily retained in underground sinks in the same way. It is always wise to refrain from drinking underground water which contains silt or clay, for although these materials in themselves are seldom injurious they may indicate the presence of surface drainage which has received little or no natural purification. It must not be inferred that all surface drainage is harmful; but it is well to bear in mind the possibilities of pollution by such drainage, and if any part of the surface drainage comes from a city or from dwellings the water should be rejected.

NATURAL PURIFICATION.

A fact which needs great emphasis is that water which flows in channels in limestone probably receives less natural purification than surface water. Especial attention is called to this fact, because there is a popular belief that water is purified by passing a short distance underground. This belief is based on a study of the purification of water by its passage through sand or sandstone. In these materials the purification is mechanical and takes place because the openings between the sand grains are very small. In other words, in removing the objectionable matter the sand acts as a mechanical filter.

Water that flows through channels in limestone receives no filtration, and consequently but little natural purification. It is also effectually sealed from the oxidizing effects of air and sunlight. The flow of water in limestone passages may be compared with its movement through ordinary water mains, and the chances for purification are about equal in the two channels.

EXAMPLE OF POLLUTION.

A typical example of the pollution of underground water in limestone is afforded by a certain city containing a spring which supplied several persons. The failure to realize the danger of pollution was due not to carelessness or negligence but to a belief that the water of the spring all came from points beyond the city limits. The important fact that underground streams have tributaries was entirely overlooked. Figure 17 gives the plan of the surface drainage of the area furnishing water to the spring *A*, which is located at the

edge of the city. There are several sinks within the city limits, and the question to be decided was whether the spring received drainage from the city through these sink holes. The depressions which received the surface drainage, outlined in figure 17, appeared to be the result of the partial collapse of cavern roofs, this fact being indicated by their general rectangular arrangement and their relation to the joint planes of the limestone. The presence of the sink holes indicated underground drainage, and it was assumed that this drainage would follow more or less closely the lines of surface drainage. The general trend of this surface drainage is toward the spring.

To test the connection between the sinks and the spring, salt was introduced into some of the sinks and its presence noted in the spring. The sinks selected for the investigation were chosen because they were supposed to include between them nearly all the area in the city which drains to the spring.

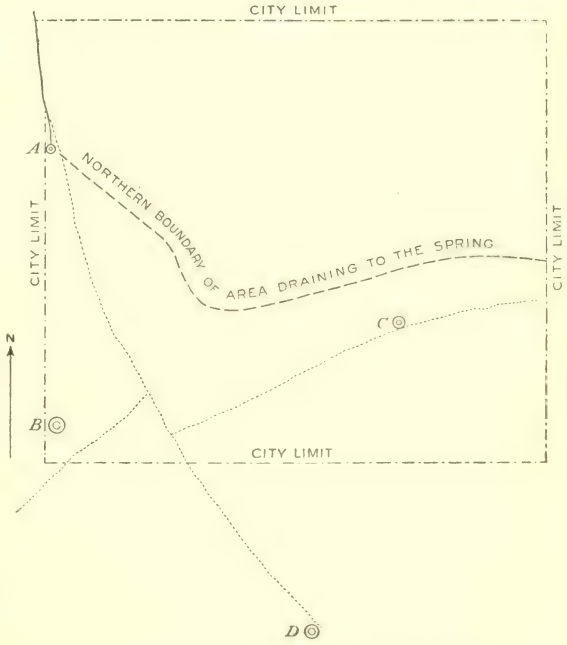


FIGURE 17.—Location of sink holes and springs.

The sink *B* is not open, and after a heavy rain it is occupied by a pool of water which seeps away rapidly. Four barrels of salt were put into this sink during a rain which lasted for twenty-four hours. Samples were then taken at the spring at intervals of one hour. The amount of chlorine in the samples was determined by means of standard silver nitrate tablets, potassium chromate being used as an indicator. Eight hours after putting the salt into the sink the amount of chlorine in the spring had doubled, and within the next two hours it rose to four times the original amount. It remained fairly uniform for several hours, finally falling to double the original amount and continuing nearly uniform for the succeeding forty-eight hours, when observations were discontinued.

The sink hole *C* had originally been open, but at the time the tests were made was filled with broken stone and loose earth. During heavy rains considerable water collected in this sink. It was

drained by means of a small passage through the loose material. The water poured into this passage at the rate of 25 to 30 gallons a minute. Two barrels of salt were put into the water which had collected in this sink after a heavy rain, and tests were made at the spring in the same manner as before. At the expiration of sixteen hours the amount of chlorine in the spring had increased 100 per cent. It rose rapidly to nearly 150 per cent above the normal and then fell with corresponding rapidity until, twenty-four hours from the time the salt was put into the sink, the amount of chlorine in the spring was only about 50 per cent above the normal.

Similar tests were made in connection with the sink at *D*, but the results were not entirely satisfactory because only 1 barrel of salt was used. However, the general trend of the underground drainage is probably toward the spring and the location of the sink *D* indicates that it is, with little doubt, connected with one of the underground channels which supplies water to the spring.

The importance of this investigation is shown by the facts that the sink *B* receives all the drainage from two houses and a barn and that the sink *C* receives a large part of the drainage of more than a score of houses. None of these houses are connected with sewers, so that the danger of pollution is very grave. In the area between *B* and *C* are a number of dwellings and the drainage of some of them is allowed to enter sink holes.

RECOMMENDATIONS.

The practice of putting rubbish, barnyard filth, etc., into sinks should be abandoned. Still more reprehensible is the custom of running sewage into sinks, thus converting the underground channels into natural sewers. This practice, which is by no means uncommon, is often defended by the assertion that the water in limestone channels beneath a city is unfit for drinking even without the sewage. The correctness of this assertion can not be disputed, but there are persons who are ignorant of the danger and who continue to use the underground water. Moreover, those living at some distance from the city may use water from the underground channel which receives the sewage. For these reasons any city which proposes to convert an underground watercourse into a sewer should be forced to trace the channel to its destination so that others may be protected.

There is need of legislation to prevent the unnecessary pollution of underground streams. Such legislation has been enacted for the protection of surface water, but the protection of underground water has been entirely neglected.

PROTECTION OF SHALLOW WELLS IN SANDY DEPOSITS.

By Myron L. Fuller.

INTRODUCTION.

Notwithstanding the exceedingly unsanitary surroundings of the driven wells in certain sandy districts which have been investigated by the United States Geological Survey, the waters in many of these wells have been found to be reasonably safe. Investigation shows this safety is due to certain definite conditions, which are the result of known laws governing the movements of ground water. It is the object of this paper to discuss these conditions and to point out their application to the sinking of shallow wells in sands receiving polluting matter at adjacent points.

SANDY DEPOSITS.

GENERAL STATEMENT.

In the eastern and northern parts of the United States deposits of sand are very numerous, widely distributed, and of considerable area, and constitute the chief source of domestic water supplies at hundreds if not thousands of points. Part of the deposits have been formed by waves along the coasts, part by winds blowing the sands from beaches and other exposed sandy areas and building them into dunes, part by deposition in glacial streams, lakes, etc., during the ice age, and part by deposition along the courses of the present rivers and smaller streams. The glacial and alluvial deposits are among the most common sites of towns, and many of even the dunes and sea beaches are occupied by populous resorts, as along the Long Island and New Jersey coasts.

In sandy regions of the type described water is generally abundant, at least in the eastern part of the United States, and commonly occurs very near the surface. For this reason shallow wells are in general use, most of them being of the driven type, although open wells are used in some of the more unprogressive districts. This is especially to be regretted, as the open porous sand readily transmits sewage and other polluting matter, much of which enters the open well through the curbing. In tubular driven wells this matter is shut off

from all except the bottom of the well, and to procure good water it is only necessary to drive to a moderate distance below the water table.

In the internal structure of sandy deposits, as determined by the character and arrangement of the materials, many variations exist, but the deposits can all be grouped under one or the other of two classes—sands of uniform character and sands with included impervious or relatively impervious layers, which need not necessarily be beds of clay, for layers of fine sand or even well-stratified layers of material of the same texture may act as confining beds.[a] The second class therefore is very large, and deposits of this type far outnumber those of the first class.

UNIFORM SANDS.

Deposits of uniform sand are limited in large measure to the wind-formed deposits known as "dunes," although certain of the more sandy glacial deposits closely approximate uniformity. The glacial deposits generally present a fairly uniform surface, but the dune areas are commonly irregular, though some rather flat-topped wind-deposited dunes are known. A smooth-topped gently sloping deposit is taken as a type in the following discussion for sake of

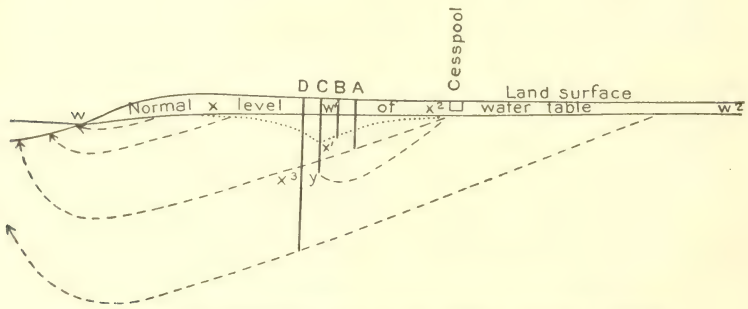


FIGURE 18.—Conditions of pollution in thick deposits of uniform materials.

simplicity. The conditions in a dune area of rolling topography would, however, be essentially the same, as the form of the water table in porous sands would be little affected by individual dunes, which are generally a minor feature of the topography.

The conditions to which wells are subject in uniform sands are illustrated in figure 18, in which the position of a cesspool and of the wells A, B, C, and D are indicated. The wells are assumed to be tubular and to draw water from the bottom only. The normal position of the water table is represented by w–w^1–w^2 and its position after pumping from well C by the dotted line x–x^1–x^2. The normal movement of the

[a] Fuller, M. L., Two unusual types of artesian flow: Water-Supply Paper U. S. Geol. Survey No. 145, 1905, pp. 41–45.

ground water is indicated by the broken lines extending diagonally downward from the water table and curving upward to points of emergence along the lake or watercourse at the left. Before any of the wells are pumped the sewage from the cesspool will follow approximately the line x^2–x^3. Under these conditions well A, which just penetrates to this line of flow, will be endangered by the polluted matter, but well B, which fails to reach the line of movement, and wells C and D, which penetrate to a point well below it, will probably be unaffected. If either of the wells is pumped vigorously the water table will be lowered in its vicinity. (Fig. 18 shows the effect of pumping well C.) The effect as regards contamination will depend on the amount pumped. Pumping well A will result in a lowering of the water table in its vicinity and an influx of water from below and from the downhill side as well as from the direction of the cesspool, but as an offset to the increased amount of pure water drawn in more sewage is likewise obtained. If well C is pumped but slightly, the quality of the water may be unaffected, but if pumped hard the water table may be lowered beneath an area extending to a point near the cesspool, the result of which will almost certainly be pollution of the well water. The effect of pumping this well, as shown in the diagram, is a lowering of the water table at the well from w^1 to x^1 and a change in the direction of the ground-water movement in its vicinity from x^2–x^3 to x^2–y, which will result in a pollution of the well. Pumping well D, though lowering the water table to a depth corresponding with x^3, will not result in pollution because of the much greater depth of the well.

Thus in uniform materials where the water is unconfined any considerable pumping of wells whose bottoms are near the lines of underflow from cesspools or other sources of polluting matter is likely to result in pollution of the well water; on the other hand, wells sunk any considerable distance below these lines of underflow are safe under ordinary conditions of pumping.

The "safety distance," as it may be called, has been the subject of much discussion. A common statement is that a well should not be located within a distance equal to one to five times its depth from any source of pollution. The application of any such rule may be far from safe, however, as an examination of figure 18 will show. The source of danger is not necessarily the nearest cesspool, but is quite as likely to be a more distant one. Well D, for instance, is safe from pollution from the cesspool shown, but would not be safe from a cesspool located at w^2.

It has been found that the depression produced in the water table by pumping has a diameter ranging from 15 to over 150 times the vertical distance which the water has been lowered, and some authorities assume that any polluting matter coming within the

limits of this depression will find its way to the well. This is probably true of open wells in general, but it is not true of driven wells nor of tightly-cased drilled or bored wells. These, though protected from the entrance of polluting matter near the surface, are, as has been explained, not safe from pollution from distant sources. So many factors, most of which are variable and generally unknown, enter into the question of the depth at which a well is safe that no general rule can be laid down. Field observations, however, seem to show that where the bottom of the well is 10 feet or more below the position of the water table when lowered by pumping the water is generally pure. A larger margin of safety should, if possible, be allowed, especially where the well is to be subjected to heavy pumping or is in a thickly settled district where many cesspools or other sources of contamination exist.

NONUNIFORM SANDS.

In the class of nonuniform sands are included both deposits consisting of alternations of sands of different texture and deposits consisting of sands with interbedded layers of finer silt.

In deposits of this nature the conditions differ greatly from those existing in uniform sands. The active circulation, instead of reaching to a considerable depth, as in uniform sands (fig. 18), is, so far as need be considered in the present discussion, restricted to zones of moderate depth (see fig. 19), in which movement is relatively rapid.

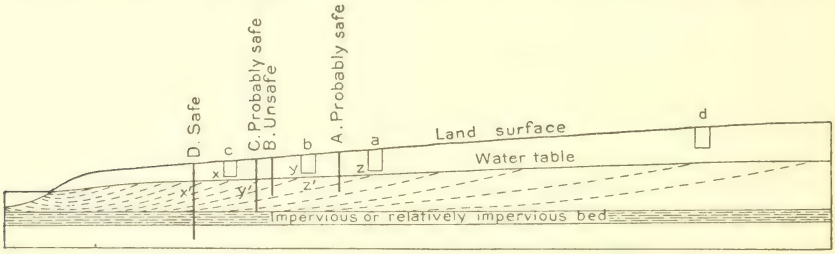


FIGURE 19.—Conditions of pollution in thin beds of sand overlying impervious layer.

The conditions shown in figure 19 may be taken as typical of those existing in nonuniform sands. The figure shows a bed of porous material overlying an impervious or relatively impervious bed, also a series of cesspools (a, b, c, d) and tubular wells (A, B, C, D) drawing water from the bottoms of the casings. The normal level of the water table is indicated and the ground-water movement is shown by broken lines. Before the wells are pumped or when only slight amounts of water are raised the ground water is essentially undisturbed and the movement of sewage from the cesspools will be approximately along the lines x–x′, y–y′, and z–z′. Under these conditions well A is probably safe, as it extends below the line of movement

from cesspool a. Well B, however, although of the same depth as well A, is probably unsafe because of the greater depth reached at that point by the polluting matter from a. At the same time well B is probably safe from pollution from cesspool b, showing again that it is not always the nearest cesspool that is the source of contamination.

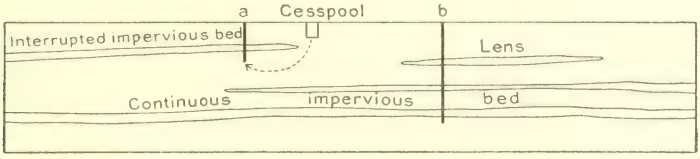


FIGURE 20.—Section showing interrupted beds and the consequent possibility of polluting matter passing underneath impervious beds.

tion. Well C, close to well B, by going deeper obtains water which is probably safe from cesspools a and b but might be polluted from a more distant source, as a cesspool at d, although the distance may be so great that all danger is eliminated. To guard against possible pollution a well should be sunk below the first impervious bed (as at well D), but even this will not always insure safety, as in many places the impervious beds are not continuous but thin out, as shown in figure 20, so that polluted waters can pass underneath them. Well b, in figure 20, passes below a continuous impervious bed and would be safe. Figure 20 also shows why the succession of beds in closely adjacent wells may be dissimilar and why the encountering of similar beds at the same depth, as at a and b, does not prove continuity.

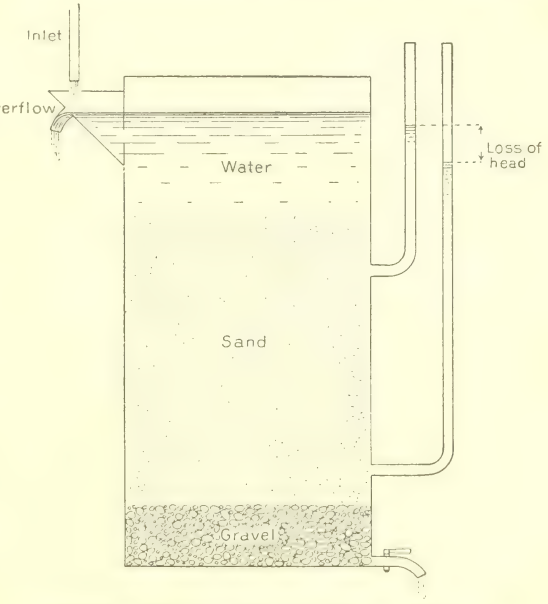


FIGURE 21.—Diagram showing loss of head by friction in column of sands. (After Hazen.)

MOVEMENT OF GROUND WATER.

Figures 18 and 19 show that water while sinking a certain distance downward spreads out to a much greater horizontal distance. That the movement is much more rapid near the surface than at greater

depths will also be apparent from a study of the conditions of motion. The flow of water through a soil of given texture at a fixed temperature and depth is proportional to the difference between the pressure head at that depth and that at the surface of the water table. The head at any deeper point will be diminished owing to the friction caused by the material between the two points. This is brought out very clearly in figure 21. The velocity of the ground-water body near the level of the water table may be many times greater than at depths of even no more than 50 or 100 feet. In fact it is probable that in many valleys and basins, especially where the materials are open and porous,

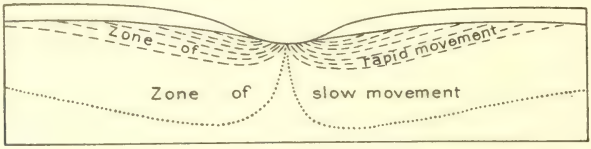


FIGURE 22.—Diagram showing concentration of motion in upper part of ground-water body.

the ground water below the level of the surface drainage is relatively stagnant, the increment due to rainfall being almost entirely removed by movements in the upper portion of the ground-water body, as shown graphically in figure 22.

The principle outlined is of great importance in considering the pollution of wells. It means that polluting matter may be carried in the upper portion of the ground-water body with greater rapidity and to a greater distance than in the portion a few feet farther down, and this suggests deepening tubular wells as a precaution against contamination.

NATURAL FILTRATION.

Types.—So-called natural filtration has been much discussed in recent years, and more or less definite ideas of its supposed applications exist in the minds of people in general as well as in those of scientists. Everyone has observed and is familiar with the effects of filtration in removing visible impurities from liquids, and many have been inclined to the belief that bacteria and even matter in solution could be removed in the same way. There are, however, for the most part, very slight grounds for such belief.

Natural filtration may be subdivided according to the character of the supposed action into mechanical, chemical, and bacteriological filtration. These are briefly considered in the following paragraphs.

Mechanical filtration.—The removal of matter held in suspension in the water constitutes mechanical filtration and is due mainly to the entanglement of the suspended particles among the grains of soil or other filtering medium through which the water passes. The efficiency of this process depends on the size and uniformity of the grains,

on the pressure head of the water which is passing through the soil, on the temperature of the water, etc. The slower the filtration the more effective it will be, hence fine material is more effective than coarse, mixtures more efficient than uniform materials, and low-pressure heads and low temperatures better than high ones.

There is no chemical purification in filtration of this nature, and in ordinary materials and with waters free from sediment there is but a relatively small decrease in the number of bacteria. Where sediment of any sort is present in considerable amounts, however, many bacteria are entangled in the filter and remain behind with the residue. Although the number thus removed may amount to a considerable proportion of the whole, if the water was originally polluted, there are almost invariably enough bacteria left to render it unsafe for drinking.

In artificial mechanical filtration through stone or other very dense media fairly perfect removal of bacteria has been effected, but under the conditions existing in nature such removal will rarely take place, except where the water passes for a long distance through fine materials. But even if bacteria will not pass through a filter with the water, they may in the course of time spread through it by multiplication, finally contaminating the water on the other side.

Chemical action.—Chemical changes in waters passing through soils are the result not of any mechanical filtering but of reactions between the water and the material with which it comes into contact. In shallow ground waters the process, instead of being one of purification, is generally one of mineralization, material being taken up from the soil instead of being left behind in it. Purification through chemical deposition is usually accomplished only at considerable depth below the surface, beyond the reach of the ordinary shallow wells. Iron, however, is occasionally deposited in small amounts between grains of sand, etc., along the contact with underlying clayey materials, even near the surface. In general the mineral matter dissolved by shallow waters is small, but in the alkaline lands of regions of slight rainfall it may be very great.

So far as the sanitary effect is concerned the most important chemical action accompanying filtration through soil is the oxidation of polluting materials. Oxygen (in air) is everywhere present in soils above the water table and, either by direct chemical action or through the influence of bacteria, attacks and breaks down the impurities, reducing them to harmless mineral compounds.

Bacteriological action.—Even more important than the oxidation of impurities by the aid of bacteria is the work done by the so-called nitrifying bacteria, which not only break down the organic polluting materials but destroy most of the disease-producing organisms. Under artificial conditions, as in filtration plants, the action is almost per-

fect, 99.5 per cent or more of the dangerous bacteria being removed; under natural conditions, however, only a relatively small fraction of the germs are affected.

General effect.—In summarizing the preceding paragraphs it may be said that in natural filtration through a moderate depth of soil the suspended impurities are in large part taken out, parts of the remainder are oxidized and their odors destroyed, and many of the bacteria are removed. The water is clear and sparkling, but as a rule it still contains unoxidized polluting matter and sufficient bacteria to make it unsafe for domestic use, except where the wells are remote from the source of pollution. The "safety distance" depends on a large number of factors, including the nature and porosity of the soil, the velocity and direction of ground-water movement, the number of sources of contamination, and the amount of pollution entering the ground.

SUMMARY AND CONCLUSIONS.

The alternation of layers of materials of different texture, even if all are pervious, and the presence of stratification planes in uniform materials tend to obstruct the downward passage of water and to confine pollution to the upper portion of the ground-water body—the part immediately below the water table. This explains why many towns located on sand deposits procure unpolluted water from driven wells sunk a few feet below the ground-water level, notwithstanding the sands receive the entire drainage of the towns. To this fact is due the absence of typhoid, cholera, and other water-borne diseases at many points where danger from pollution might be supposed to exist. To insure safety wells should be carried to a considerable depth below the ground-water level, and as each succeeding layer of material affords additional security they should be sunk as deep as possible.

Polluted ground waters are more or less purified through the removal of their suspended matter and a portion of their bacteria by entanglement among the grains of the material through which they pass, by oxidation, and by nitrifying bacteria, but more or less polluting matter remains for a considerable length of time.

The distance to which pollution is carried will depend on the porosity and size of grain of the materials through which it passes, the amount of rainfall, the inclination of the surface and the elevation of the outlet, the temperature, the number of sources of contamination, and the amount of pollution entering the ground.

Where a single source of pollution exists and only a small amount of polluting matter enters the ground the contamination does not commonly extend beyond 150 feet. An open well at this distance would probably give no trouble, and a driven well extending 15 feet or more below the water level is almost sure to be safe, providing the rate of movement of the ground water is normal and the pumping not severe.

Where there are several sources of pollution and large amounts of polluting matter are introduced into the ground the contamination may extend in porous materials for some hundreds or even thousands of feet,[a] especially when the underground waters move with considerable velocity. In such places open wells are out of the question, but driven wells carried 20 or 25 feet below the water level will usually afford safe water if not heavily pumped. If the wells are heavily pumped to obtain water for manufacturing purposes or for city supply the water table is usually lowered considerably, the polluted waters likewise sinking to a greater depth. Under such conditions a depth of 50 feet or more below the normal water table is none too much.

[a] Dole, R. B., Use of fluorescein in the study of underground waters: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, p. 81.

COMPOSITION OF MINERAL SPRINGS IN MAINE.

By Frederick G. Clapp.

INTRODUCTION.

Many analyses of mineral-spring waters from Maine and other States have been published from time to time, but no effort has been made to give a summary of the chemical characteristics of spring water in any particular area. Field work done in an investigation of the underground waters of Maine in 1906 and subsequent office work, in which practically all the chemical analyses made of waters in that State were compiled, has enabled the writer to get together much material showing the character of the spring waters, and a summary of the work done is here presented. In the detailed report on this investigation[a] the numerous springs are described and information concerning the character of the water and the volume of the flow, and other facts of interest are presented. For that reason only a brief summary of the composition of the waters will be given here.

SPRINGS OF MAINE.

Number and importance.—Springs are abundant in Maine, especially in the interior of the State. Many of them are situated on hillsides, from which the water can be distributed by gravity to residences and farms. In places several families have combined to have the water of the larger springs distributed through their dwellings by pipes. Here and there the water is raised by windmills.

The water is very cool, temperatures as low as 45° being common, and temperatures over 50° rarely being reported. This low temperature makes the spring waters valuable for use in dairies and creameries.

In those parts of the State where the well water is hard, springs are more generally utilized than where it is soft. In a few places, where the quality of water in the neighboring streams is poor, springs supply manufacturing establishments.

The earliest published work on the mineral springs of Maine was the report by Goodale, issued in 1861.[b] The data contained in this

[a] Clapp, F. G., Underground waters of southern Maine: Water Supply Paper U. S. Geol. Survey No. 223, 1908.

[b] Goodale, G. L., Report on the mineral waters of Maine: Sixth Ann. Rept. Maine Bureau Agr., 1861.

report, consisting of a few analyses, statistics of temperature, etc., were compiled by Peale[a] in 1886. A few springs were described in 1899 by Crook.[b] Otherwise no information has been published regarding Maine springs except the reports of sales of spring waters given in the Geological Survey's annual reports on the mineral resources of the United States.

Commercial springs.—A group of springs of great economic value to the State comprises those which are designated commercial springs, or those of which the waters are sold by measure. In this group there are two subclasses. The first includes springs that furnish table water to consumers in their vicinity at regular intervals. The second subclass comprises springs the waters of which are bottled and shipped to distant points, springs whose waters are commonly supposed to possess medicinal properties, and certain others whose waters are exceptionally pure.

The springs reporting sales in southern Maine at the time this investigation was made were 44 in number, as follows:

Addison Mineral Spring, Addison, Washington County.
Arctic Spring, Bangor, Penobscot County.
Baker Puritan Spring, Old Orchard, York County.
Bluehill Mineral Spring, Bluehill, Hancock County.
Carrabasset Mineral Spring, Carrabasset, Franklin County.
Chapman's Spring, Brewer, Penobscot County.
Cold Bowling Spring, Steep Falls, Limington, York County.
Crystal Mineral Spring, Auburn, Androscoggin County.
Forest Spring, Litchfield, Kennebec County.
Glenrock Mineral Spring, Greene, Androscoggin County.
Glenwood Spring, St. Albans, Somerset County.
Highland Spring, Holden, Penobscot County.
Highland Mineral Spring, Lewiston, Androscoggin County.
Hillside Spring, Bangor, Penobscot County.
Indian Hermit Mineral Spring, Wells, York County.
Ishka Springs, West Hancock, Hancock County.
Katagudos Spring, Eastbrook, Hancock County.
Keystone Mineral Spring, East P[illegible]nd, Androscoggin County.
Knowlton's Soda Spring, South [illegible]ng, Franklin County.
Mount Desert Spring, Bar Harbor, Hancock County.
Mount Hartford Mineral Spring, Hartford, Oxford County.
Mount Oxford Spring, Sumner, Oxford County.
Mount Zircon Spring, Milton Plantation, Oxford County.
Oak Grove Spring, Brewer, Penobscot County.
Old Yorke Spring, Old Orchard, York County.
Oxford Spring Home, Oxford, Oxford County.
Paradise Spring, Brunswick, Cumberland County.
Pejebscot Spring, Auburn, Androscoggin County.
Pine Spring, Topsham, Sagadahoc County.
Pine Grove Spring, Pittsfield, Somerset County.
Poland Spring, Poland, Androscoggin County.

[a] Peale, A. C., Mineral waters of the United States: Bull. U. S. Geol. Survey No. 32, 1886, pp. 13–16.
[b] Crook, J. K., Mineral waters of the United States and Canada.

Pownal Spring, New Gloucester, Cumberland County.
Pure Water Spring, Waterville, Kennebec County.
Raymond Spring, North Raymond, Cumberland County.
Rocky Hill Spring, Fairfield, Somerset County.
Sabattus Mineral Spring, Wales, Androscoggin County.
Seal Rock Spring, Saco, York County.
Sparkling Spring, Orrington, Penobscot County.
Switzer Spring, Prospect, Waldo County.
Thorndike Mineral Spring, Thorndike, Waldo County.
Ticonic Spring, Winslow, Kennebec County.
Underwood Spring, Falmouth Foreside, Cumberland County.
Wawa Lithia Spring, Ogunquit, York County.
White Sand Spring, Springvale, York County.

In addition to the springs listed above, the following were reported by Peale,[a] with analyses that were made at various dates between 1861 and 1879. It is not known whether these springs are still in use, but they do not report sales:

American Chalybeate Spring, South Auburn, Androscoggin County.
Auburn Mineral Spring, South Auburn, Androscoggin County.
Boothbay Medicinal Spring, East Boothbay, Lincoln County.
Ebeeme Spring.
Fryeburg Spring, Fryeburg, Oxford County.
Lake Auburn Mineral Spring, North Auburn, Androscoggin County.
Lubec Saline Springs, head of Lubec Bay, Washington County.
North Waterford Springs, northwest of Waterford village, Oxford County.
Poland Silica Springs, South Poland, Androscoggin County.
Rosicrucian Springs, Rosicrucian, Lincoln County.
Samoset Mineral Springs, Nobleboro, Lincoln County.
Scarboro Spring, Scarboro, Cumberland County.
Summit Mineral Spring, Harrison, Cumberland County.
West Bethel Spring, West Bethel station, Oxford County.

Analyses of some of the above were taken by Peale from Goodale's report.

Origin of spring waters.—A common but erroneous belief regarding spring waters is that most of them are derived from a distant source. Several spring owners have told the writer that the water from their springs came from the White Mountains, at least 40 or 50 miles distant. Owners of flowing wells in Islesboro have stated their belief that the water of the wells had its source in mountains on the mainland several miles distant.

In certain regions springs may have such an origin. The waters of many mineral springs in the West come long distances underground. In Maine, however, so far as known, no spring or well obtains its supply at a distance of more than a mile from the place where the water emerges. Most spring waters enter gravel deposits on the surface of a hill and find their way downward along the top of the bed rock or hardpan deposits until they find an easy point of

[a] Op. cit.

emergence on the slope. The waters of a few mineral springs issue from joint cracks or from fissures in rock. These waters may come from a considerable depth, but as their temperature is generally about the normal temperature of the region they probably do not come from a greater depth than 100 feet below the surface.

QUALITY OF WATERS.

CLASSES.

The waters of the mineral springs of Maine are mostly of the classes known as "neutral" and "light alkaline-chalybeate." There are, however, a few strong chalybeate waters and several which might be ranked as saline-chalybeate.

NATURE OF ANALYSES.

Sources.—The analyses given on page 74 may be divided into three classes, according to their sources: First, those made by Prof. F. C. Robinson, some of them for the United States Geological Survey, in connection with underground-water investigations; second, those made by Dr. W. W. Skinner, of the Bureau of Chemistry, United States Department of Agriculture, in cooperative work between that bureau and the United States Geological Survey; third, those made by other persons and collected in field work and through correspondence.

In all 75 analyses of Maine mineral waters have been made by about 25 different chemists. Some of these analyses are very reliable; others are less certain.

Variations.—The compilation of the results showed more or less important discrepancies in a few analyses made by different chemists on the same spring water. For example, the water of the Poland Spring, which has probably been analyzed more times than any other spring water in Maine, was reported by different chemists to contain total solids ranging in amount from 63 to 108 parts per million. Two analyses of Pine Spring, in Topsham, both by reliable chemists, show 13 and 33 parts per million of total solids; and the several constituents are similarly diverse in amount. This variation in the composition of the water is due to differences in the season or year when the samples were taken; to their collection at some abnormal time, as immediately after a storm or during a dry period; to variations in chemical manipulation; or perhaps to the fact that the water has stood in bottles for a considerable time before analysis, a factor which may be of some importance.

Forms.—As the chemists of the country have not agreed on any uniform method of reporting analytical results, the analyses collected from different sources were found to vary greatly in form.

In some the results were stated in parts per million, a method which is now generally recognized as the most scientific. In others they were given in grains per gallon, a form of statement that appeals most to laymen. In some they were reported in parts per 100,000 and in some as parts per 10,000. A few analyses, as those made for the Geological Survey and those made by the Bureau of Chemistry, are stated in ionic form. In the many miscellaneous analyses collected from different sources, however, the various elements are commonly grouped together in the forms in which the analyst has thought them to be combined in nature, and the resulting compounds are reported; this method is now generally recognized as misleading, because no chemist can say definitely in what form a certain group of elements is combined in a water. In order to reduce all the analyses to a standard basis which would permit their direct comparison, they were recomputed, mostly by R. B. Dole, of the United States Geological Survey, into parts per million and into the ionic form, and they are so given in the table (p. 74).

Errors.—The investigations in Maine brought to light the fact that errors appear in many analyses of mineral waters published in circulars issued by the owners and in reports of various kinds. These errors are not usually due to intentional misstatements by the owners, some of them being simply printer's errors, in which the decimal points are transposed and chemical terms misspelled, the result being that the analysis shows a compound entirely different from the one it was intended to report. The analysis of one prominent mineral spring in Maine reports "carbonate of iron," whereas what was meant was carbonate of lime. Another circular received by the writer and submitted to the analyst for verification was found to contain three mistakes in the figures.

A defect in some analyses is the omission of any statement indicating the form in which the figures are reported, whether in "grains per gallon," in "parts per million," or in some other form. Of course such an omission renders an analysis valueless.

RANGE IN COMPOSITION.

Total solids.—A study of the 75 analyses of mineral springs shows that the waters vary widely in composition. The total solids run from 11 to 425 parts per million, the lowest figures being found in the spring at Paris Hill, in Oxford County. The water of Pine Spring, in Topsham, Sagadahoc County, which was analyzed by Robinson, shows only 13 parts per million of total solids. The third spring in Maine in respect to mineral purity is Paradise Spring, in Brunswick, Cumberland County, for which Robinson and Carmichael report 17 and 18 parts per million of total solids, respectively. The springs of the Paris Hill Water Company are believed to issue from bowlder

clay; Pine Spring and Paradise Spring, situated only a mile apart, on opposite sides of Androscoggin River, issue from sand and gravel overlying clay.

So far as known, the highest mineral content of the springs in Maine is found in the Samoset Mineral Spring, in Nobleboro, Lincoln County. The total solids found in this spring, as reported by Carmichael, are 425 parts per million.

Silica (SiO_2).—The maximum and minimum amounts of the various constituents are not always found in the same springs as those which show the maximum and minimum amounts of total solids. For instance, although the lowest amount of silica (1.2 parts per million) is found in the spring of the Paris Hill Water Company, which shows the lowest total solids, the amount found in the Samoset Mineral Spring, the highest in total solids, is only 12 parts per million, considerably less than the highest amount of silica found in the State. According to the analyses, the spring highest in silica is the Bluehill Mineral Spring, in Hancock County, where 21 parts per million were found. Next to this come the Pejepscot, Windsor, and Poland springs, situated in Auburn, Lewiston, and Poland, in Androscoggin County, only a few miles apart, in which there are 18 and 19 parts per million of silica. Two of these springs can be seen to issue from gneissic rock, and it is probable that rock lies not far below the surface in the third. The lowest proportions of silica are found in springs that issue from bowlder clay and gravel. An interesting feature is that two fairly high reports of silica, 15 and 15.5 parts per million, were found in a spring in the bottom of a limestone quarry at Rockland, Knox County, and in the Pine Grove Spring, near Bangor, notwithstanding the fact that both these springs issue from calcareous rocks.

Organic and volatile matter.—The organic and volatile matter, as reported by reliable chemists, ranges in the springs of Maine from 2.1 to 28 parts per million. The highest report, strange as it may seem, comes from a spring in the bottom of a limestone quarry at Rockland, Knox County, 70 feet below the surface of the ground. The lowest amount is from the spring of the Paris Hill Water Company. A few analyses report organic and volatile matter as absent, but as the complete analyses that have been made show small amounts of these materials, it is probable that the analyses reporting none are in error.

Iron and aluminum oxides ($Fe_2O_3 + Al_2O_3$).—Iron and aluminum oxides range from a trace, reported in several springs, to 8.9 parts per million in the spring in the quarry at Rockland. A comparatively small number of the analyses report iron and alumina, however. It is not known exactly what is meant by the word "trace," but some reports give it as low as 0.

Iron (Fe).—Where iron has been tested separately from aluminum, it has usually been found to be absent, and where present is as a rule not

over 1 part per million. The highest amounts reported are 19 and 20 parts per million, in the Samoset Mineral Spring and the Boothbay Medicinal Spring, but as alumina is not reported in these springs, these figures may include that also. The highest amount of iron reported in an analysis where alumina is reported separately is 3.1 parts, in the Bluehill Mineral Spring, which tastes very strongly of iron.

Calcium (Ca).—The lowest amount of calcium reported in Maine is found in the springs of the Paris Hill Water Company. The largest amount is 42 parts, reported in two springs—the Ticonic Mineral Spring, in Waterville, and the Windsor Mineral Spring, in Lewiston. The rocks in these places are not particularly calcareous, and it is somewhat surprising that the calcium should be so much higher than that in the limestone spring at Rockland, which shows only 29 parts.

Magnesium (Mg).—Magnesium is reported absent in several analyses, but as these were not complete the accuracy of the reports can not be vouched for. The lowest reliable report is 0.05 part, in the spring of the Paris Hill Water Company. The highest magnesium reported is 22 parts per million, in the spring in the limestone quarry at Rockland. It is rather interesting to note that in this spring the magnesium amounts to 80 per cent of the calcium found. In most Maine springs the magnesium is below 3 parts per million.

Sodium (Na).—Sodium ranges from 1 part per million in the Carrabassett Mineral Spring, in Franklin County, and the Mount Zircon Spring, in Oxford County, to 19.6 parts in the spring in the limestone quarry at Rockland.

Potassium (K).—In the Rock Hill Spring, in Fairfield, Samoset County, and the Vienna Sparkling Spring, at Vienna, Kennebec County, the amount of potassium is reported as only 0.4 part. From this figure it ranges to 15 parts in the Boothbay Medicinal Spring, at East Boothbay. The potassium in the Samoset Mineral Spring is not reported. Potassium is generally less in amount than sodium, but the Mount Zircon Mineral Spring contains 9.8 parts of potassium and only 1 part of sodium.

Bicarbonate radicle (HCO_3).—As no waters have been analyzed which are known to contain natural carbonates, it is believed that all the carbonates in underground waters in Maine exist in the bicarbonate form. The amount of bicarbonates ranges from 1.14 parts per million in the Raymond Spring, at North Raymond, Cumberland County, to 157 parts in a spring at Brewer, Penobscot County. The latter determination is not from a laboratory analysis, and for that reason the figures are not absolutely trustworthy. The highest amount found in analyses made by reliable chemists was 73 parts, in the Oak Grove Spring, at Brewer.

Sulphate radicle (SO_4).—In a number of the analyses and assays sulphates are reported to be absent. In complete analyses they are generally reported as present, though in small quantities, and for that reason it is believed that they are probably present in all these waters. They range from less than 1 part per million in several springs to 37 parts in the Samoset Mineral Spring, Nobleboro.

Chlorine (Cl).—As would be expected, the amount of chlorine is dependent to a certain extent on the normal chlorine of the region, the lowest chlorine being found in springs in the interior of the State rather than in those near the coast. It is also dependent, however, on the presence or absence of surface pollution and on the character of the formation from which the water issues. The smallest amount reported from the mineral springs in Maine is 0.8 part per million in the Mount Zircon Mineral Spring, in Oxford County. Another chemist, however, reports the amount in this spring as 1.5 parts per million. Several other springs report less than 1 part per million, and from these small amounts it ranges to 60 parts per million in the Sparkling Spring in Orrington, Penobscot County. In well waters chlorine was frequently found to be much higher, independently of the normal chlorine of the region.

Hardness.—Few mineral springs have been tested for hardness, but according to the data at hand it seems to range from 1 to 26 parts per million. Probably, however, it is much higher than this in the regions of calcareous slates in northeastern Maine.

Other elements.—Few of the rare elements are reported in the Maine mineral springs, but this is possibly due in part to the fact that few have been sought. Aside from those mentioned above, the most common constituent tested for is lithium, which occurs in several springs; but with one exception it has been reported either as a "trace," a "minute trace," or "absent." The exception is the Wawa Lithia Spring, at Ogunquit, York County, in which 3 parts per million of lithium was reported, but this figure has not been verified.

RESULTS OF ANALYSIS.

The waters of over 50 mineral springs in Maine have been analyzed, and figures showing the composition of most of them are given in the detailed report on the underground waters of southern Maine.[a] From these has been compiled the following table, giving the observed maxima and minima of each of the principal substances contained.

From the same paper a number of analyses, representing typical spring waters from each county, have been selected and are pre-

[a] Clapp, F. G., Water-Supply Paper U. S. Geol. Survey No. 223, 1908.

sented in the following table for the purpose of showing the general character and range of composition of the various waters:

Range in composition of Maine spring waters.

[Parts per million.]

	Maximum.	Minimum.
Organic and volatile matter	28	2.1
Chlorine (Cl)	60	.8
Silica (SiO_2)	19	1.2
Oxides of iron and aluminum ($Fe_2O_3+Al_2O_3$)	9	Trace.
Calcium (Ca)	42	1.2
Magnesium (Mg)	22	.05
Sodium (Na)	127	1.0
Potassium (K)	15	.4
Bicarbonate radicle (HCO_3)	157	.14
Sulphate radicle (SO_4)	37	.00

Selected analyses of waters of mineral springs in Maine.

[Including typical waters from each county.]

No.	County.	Locality.	Owner.	Name of spring.	Total solids.
1	Androscoggin	South Poland	Hiram Ricker & Sons	Poland Spring	108.651
2	Cumberland	Brunswick		Paradise Spring	18.0
3	Franklin	Carrabassett	Carrabassett Mineral Spring Co.	Carrabassett Spring	72.0
4	Kennebec	Litchfield	Forest Springs Water Co.	Forest Spring, No. 1	[a]100.0
5	Knox	Rockland		Spring in bottom of limestone quarry.	234.2
6	Lincoln	Nobleboro		Samoset Mineral Spring	425.0
7	Oxford	Milton plantation.	Mount Zircon Spring Co.	Mount Zircon Mineral Spring.	[b]33.0
8	.....do.....	Paris	Paris Hill Water Co	Crocker Hill Spring (public supply).	[a]11.0
9	Sagadahoc	Topsham	Pine Spring Water Co.	Pine Spring	13.0
10	Washington	Harrington	Quantabacook Water Co.	Harrington (public supply)	70.0
11	York	Old Orchard	Olde Yorke Springs Co.	Olde Yorke Spring	94.0

No.	Organic and volatile matter.	Silica (SiO_2).	Iron and aluminum oxides ($Fe_2O_3+Al_2O_3$).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Chlorine (Cl).	Carbonate radicle (CO_3).	Material.	Analyst.
1	.....	15.40	.....	.....	14.37	2.38	6.34	0.90	55.63	3.29	5.90	.....	Granite.	W. W. Skinner.[c]
2	0.34	6.6	.....	0.09	.68	.28	2.8		.....	1.0	1.6	4.2	Gravel	F. C. Robinson.
3	.....	14.0	5.3	.....	8.2	4.3	2.8	1.6	.....	16.0	4.4	15.0	...do..	Salvatore La Bua.
4	3.0	14.0	.....	Tr.	22.0	1.6	5.3	2.7	.....	9.0	3.0	38.0	...do...	F. C. Robinson.
5	28.2	15.0	8.9	.....	28.8	22.4	19.6	4.7	.....	29.1	6.1	.....	Limestone.	Do.
6	Tr.	12.0	.....	19.0	23.0	1.9	127.0	.....	.....	37.0	11.0	192.0	.....	H. C. Carmichael.
7	2.2	9.7	.....	.66	2.3	.....	1.0	9.8	.....	5.4	1.5	.....	Till...	F. L. Bartlett.
8	3.7	1.2	.33	.....	.51	.05	1.8		.....	.....	3.9	.....	...do...	
9	.....	4.6	.....	.33	1.0	.03	2.0		.....	.2	2.3	3.1	Gravel	F. C. Robinson.
10	11.9	13.1	1.2	.....	16.6	1.8	6.0	1.1	.....	6.5	9.0	.....	...do...	Do.
11	.....	4.2	.....	.06	14.0	3.5	11.0	5.8	.....	8.2	12.0	34.0	.....	Do.

[a] Including lithium, trace.

[b] Including aluminum, trace.

[c] Analysis made in cooperative work between United States Geological Survey and Bureau of Chemistry. The following substances were also found: PO_4, trace; BO_2, none; NO_3, 3.98; NO_2, none; bromine, none; iodine, none; Fe and Al, 0.32; Mn, none; Li, none; NH_4, 0.011; oxygen to form Fe_2O_3 and Al_2O_3, 0.130.

SALINE ARTESIAN WATERS OF THE ATLANTIC COASTAL PLAIN.

By Samuel Sanford.

INTRODUCTION.

Extent.—The land area of the Atlantic Coastal Plain stretches from New York Harbor to the Florida straits. East of New York, except for patches, such as Long Island, Block Island, and the islands of Buzzards Bay and of the east coast of Massachusetts, the coastal plain is almost completely covered by water, its underwater extension reaching to the edge of the Banks of Newfoundland, nearly a thousand miles beyond Boston. This paper treats of underground waters in a strip of the plain extending from New York to Florida, about 800 miles in an air line, with a width gradually increasing from 20 miles at Sandy Hook to 63 miles at Cape May, 72 miles at Cape Charles, 175 miles at Cape Hatteras, and 135 miles at Charleston.

Geology.—The Coastal Plain is underlain by a great succession of sedimentary deposits, mostly unconsolidated, consisting of gravels, sands, clays, marls, and loams. In places the sands and clays are indurated enough to form sandstones and shales. In places also the marl beds are so full of shells and calcareous débris that they form lime rocks. No solid limestones (limy beds compact enough to be used as building stone) occur north of the Virginia-North Carolina line, but south of it, in North Carolina, South Carolina, and Georgia, some of wide extent are found. All the members of the great succession of deposits have a general east or southeast dip, the inclination being measured in feet per mile rather than in degrees, and all overlie a floor of crystalline rock that dips seaward at a slightly greater angle. This floor was once a peneplain, a rock surface reduced by the action of streams through thousands of years to an almost uniform slope. A general subsidence carried it below the level of the ocean and the Coastal Plain sediments were gradually deposited upon it. This peneplain, however, was not perfectly flat, but had within distances of a few miles differences of elevation of 100 or 200 feet, many of which were not obliterated by the advancing sea. Neither was the sedimentation continuous. At times the land rose, the sea retreated, and the sediments that had accumulated were eroded. In

the course of alternate depressions and elevations of the land the bed rock was gently bowed or warped, so that some places were more deeply eroded in retreats of the sea and more thickly covered in advances than others. Because they lie on such a lumpy, irregularly warped floor the total thickness of the deposits at points equally distant from the western margin varies decidedly.

Few wells near the coast have been sunk to this crystalline floor, but the deep drilling that has been done indicates that the Coastal Plain sediments at Atlantic City, N. J., are probably 3,000 feet thick; at Ocean City, Md., and near Franklin City, Va., possibly 3,500 feet; and at Charleston, S. C., perhaps 2,500 feet. At Fort Monroe, Va., the total thickness is known to be 2,250 feet and at Fort Caswell, N. C., 1,540 feet.

ARTESIAN WATERS.

Occurrence.—As the deposits of the Coastal Plain are largely unconsolidated and include many sandy beds outcropping in a region of copious rainfall and having a general seaward dip, they contain great stores of artesian water, which are, possibly, the most valuable underground resource of the area under consideration. This resource has been extensively developed in the last twenty years and hundreds of wells are sunk annually. Though all the water-bearing beds have not been found, enough work has been done in New Jersey to demonstrate the existence in that State of potable water at fully twelve horizons of wide extent. At least six water-bearing sands occur in Maryland and Virginia, and there are probably as many in North Carolina, South Carolina, and Georgia.

Quality.—In Virginia and the States to the north the beds yield water that is prevailingly soft—that is, water that contains only small amounts of lime and magnesia. In North Carolina and South Carolina, though soft waters probably predominate in deep-lying beds, hard waters are of wide occurrence, particularly at depths of less than 300 feet. Whether hard or soft, however, the true artesian waters, those which rise notably in the well when a water bed is pierced, are as a rule derived from sources that are beyond the possibility of contamination by surface impurities, and, being germ free, they are usually better for drinking than the easily polluted supplies obtained from dug wells. They have been used chiefly for domestic purposes at individual dwellings, but also for public-supply systems and by railroad companies and many manufacturing concerns.

Development.—Most of the wells drilled are of small diameter, 1 inch to 2 inches, and cost from $10 to $100, but many of larger diameter, costing from $500 to over $5,000, have been put down, and the number of these is increasing. It is safe to say that fully 10,000 artesian wells costing from $10 to $38,000 have been sunk in the Coastal Plain, and that the total investment in such wells exceeds $1,000,000.

SALINE WATERS.

GENERAL STATEMENT.

Though most of the Coastal Plain flows are adapted for household use and some make excellent boiler water, at a number of places flows have been tapped, mostly at depths of several hundred feet, which are called brackish or salt. Most of these are poor boiler waters and some are not suited for drinking, except for their medicinal value. Owing to a widely held opinion that where salt water has been struck fresh water can be obtained by sinking to some particular underlying formation, or by drilling deep enough, an attempt is made in this paper to summarize the essential data collected by the Geological Survey on the occurrence of saline flows and the position and extent of beds yielding salt water.

Many thousands of dollars have been spent in fruitless exploration for fresh water in salty areas, one deep well at Fort Monroe having cost the Government nearly $35,000; and the growing interest in artesian supplies and the rapid increase in the number of wells indicates that much time and money may be wasted in similar attempts in the immediate future. Hence it is desirable that well drillers and persons contemplating drilling should be informed of doubtful localities and the probabilities in such places.

DEFINITION OF SALT WATER.

The question what is a salt water can be variously answered, but here it is assumed to be a water having a salt or brackish taste. Estimates of the amount of common salt (sodium chloride) that in solution will give such a taste vary widely, different chemists stating the proportion at 500 to 1,200 parts per million of water. A factor of importance in natural waters is the effect of other substances in solution. A water high in sodium chloride but containing much sodium bicarbonate (a substance that is present in large amount in many deep flows in the Coastal Plain), is much pleasanter to the taste than a water which contains an equal amount of sodium chloride, but in which the sodium bicarbonate is replaced by calcium bicarbonate, the predominating mineral substance in many shallow flows. The standard, therefore, must be more or less arbitrary. The accompanying table includes data from (1) all localities where artesian water has been called salt and where no analyses have been made, and (2) all places where analysis has shown the waters to contain more than 800 parts per million of sodium chloride (equivalent to 500 parts of chlorine). The summarized data relate to one or more wells in every area where salt water has been reported at a depth of more than 100 feet. Wells less than 100 feet deep are not included, because shallow brackish waters resulting from the direct entrance of sea water to the beds do not have any necessary relation to the deeper waters under consideration.

Saline wells in the Atlantic Coastal Plain.

Locality.	Date.	Depth (feet).	Depth main salt-water horizon (feet).	Yield (gallons per minute).	Salinity (parts per million of chlorine).	Age of saline beds.	Waters above main salt-water horizon.	Waters below main salt-water horizon.	Remarks.
NEW JERSEY.									
Cape May County:									
Cape May Point.	1879	224	224	.....	Salt.....	Miocene.....	.....	.....	Abandoned; other wells get good water at 320–360 feet.
Wildwood.....	1900	326	10 to 260	Strong flow.	...do.....	Quaternary; Miocene (?).	Fresh water at 75 and 101–106 feet; salt water at 215 feet.	Fresh water at 290 and 326 feet.	Water from 290 feet used.
Do.....	1894	1,244	1,185	...do...	...do.....	Eocene.....	Fresh water at 75, 625, 845, and 930 feet.	.....	Fresh water from 930 feet used.
DELAWARE.									
Sussex County:									
Lewes	1898	1,080	1,080	38.....	Very salt	Pamunkey.....	Salt water at 891 and 950 feet; fresh water at 400, 625, and 750 feet.	.....	Abandoned.
MARYLAND.									
Anne Arundel County:									
Thompsons Point.	1908	300	150	.....	.....	Potomac.....	Fresh water at 25–100 feet	.....	Water below 100 feet too salt for use.
Worcester County:									
Pocomoke.....	1900	496	225	.....	Salty....	Chesapeake.....	Good water at 75–85 feet; hard water at 120 feet.	Salty water at 290 feet; salt sulphur water at 485 and 495 feet.	Water used from 195–225 and 247–290 feet.
Do.....	1907	1,500	480	[a] 25...	1,180....	.....do.....	.....do.....	Fresher water at 1,200 feet and below.	Water from 1,200 feet and below used occasionally.
VIRGINIA.									
Accomac County:									
Onancock.....	1894	480	140	Small.	Brackish	Chesapeake	Fresh water at 16, 30, and 50 feet.	No water below 140 feet.....	Abandoned.
Tangier Island.	1904	250	140	...do.....	...do.....	.....do. (?).....	Fresh water at 85 feet.....	.....do.....	Water from 85 feet used.
Elizabeth County:									
Fort Monroe...	1902	2,250	1,320	.....	Very salt	Potomac.....	Salt water at 285, 630, and 980 feet.	Very salt water at 2,131 feet.	Never used.
Hotel Chamberlin.	1896	945	945	25.....	[b] 4,978..	.....do.....	.....	.....	Used for flushing.
Gloucester County:									
Achilles.....	1902	610	610	[a] 1.....	[b] 1,400...	Pamunkey.....	Water at 450 feet.....	.....	Domestic use.

Do	1904	570	570	a ½	b 1,570	do	do		Do.
Roanes	1898	716	716	a 52	b 1,630	Marine Cretaceous	Water at several horizons		Used for washing.
Do	1894	850	850	a ½	b 1,100	Potomac			
Severn	1902	610	575	a ½	b 2,500	Pamunkey	Fresh water at 8, 24 feet; water at 504 feet.	Water at 610 feet	Little used.
Mathews County:									
Fitchetts	1904	110	110			Chesapeake	Slightly brackish water at 50 feet.		Water from 50 feet used in boiler.
Norfolk County:									
Lambert Point	1890	616	610	a 65	b 292	Marine Cretaceous			Used for drinking and washing.
Northampton County:									
Bone Island		169	169		610	Chesapeake (?)			Domestic use.
Cherrystone Island	1899	240	240(?)	a 10–80		do			Boiler supply.
Princess Anne County:									
Moores Bridges	1898	1,760	1,072	a 150	b 1,700	Potomac	Salt water at 738, 783, 805, 950, 975, 984, and 1,038 feet.	Salt water at 1,190, 1,220, 1,227, 1,480, and 1,760 feet.	Well dynamited; present flow salt sulphur water from unknown depth.
NORTH CAROLINA.									
Beaufort County:									
Washington		360+	360+		Salt (?)	Marine Cretaceous			Abandoned.
Brunswick County:									
Quarantine Station	1896	400	400	a 8,800–235		do			
Wilmington	1899	1,330	1,019	a 7,400		do	Hard fresh water at 1,000 feet; brackish water at 379, 496, 518, 574, and 990 feet.		Lowest chlorine after pumping one hour.
Columbus County:									
Cronly		278	278(?)	a 747					Little used.
Craven County:									
Newbern		353	300	100	Very salt	Marine Cretaceous			Not used.
Hyde County:									
Fairfield			220–280		b 2,860	Miocene	Fresh water at 80 feet		Abandoned.
Swanquarter			260+			do			Do.
New Hanover County:									
Castle Hayne	1906	370	340	Large flow.	Very salt	Marine Cretaceous	Hard, fresh water at 10 and 93 feet; salt water at 270 and 338 feet.		Do.
Fort Caswell	1907	1,542	1,440		10,400	do (?)	Water at 100 feet		Not used.
Do	1902	836	836	2	b 7,840	do	Salt water at 365, 719, and 800 feet.		Do.

a Flow at surface.

b Analyzed in 1906.

Saline wells in the Atlantic Coastal Plain—Continued.

Locality.	Date.	Depth (feet).	Depth main salt-water horizon (feet).	Yield (gallons per minute).	Salinity (parts per million of chlorine).	Age of saline beds.	Waters above main salt-water horizon.	Waters below main salt-water horizon.	Remarks.
NORTH CAROLINA—continued.									
Pasquotank County:									
Canaan	1903	615	300	Very salt.	Very salt	Miocene	Hard water at 14, 36, 60, and 260 feet.	Salt water below 300 feet	Abandoned.
Elizabeth City		300+	300+			do	Hard water at 250–300 feet	Salt water somewhere below 300 feet.	Do.
Tyrrell County:									
Columbia			348		Salt (?)	do			Do.
SOUTH CAROLINA.									
Beaufort County:									
Beaufort			500(?)			Eocene (?)			
Folly Island			500(?)			do			
Port Royal Island.			500(?)			do			
St. Helena Island.			500(?)			do			
Charleston County:									
Charleston	[a]1868	1,260	1,250		715	Marine Cretaceous			
Do	[a]1879	1,970	1,950		121	do	Water at 960, 1,000, 1,557, 1,590, 1,862, and 1,880 feet.		Domestic use.
Do	[a]1880	425	425(?)		1,486	do			
Do	[a]1877	380	380		[b]2,300	Eocene (?)			

[a] Date of analysis.

[b] Estimated.

SALT-WATER AREAS.

As the table shows, no deep salt waters have been recorded in the Coastal Plain in New Jersey, except at Cape May Point and Wildwood, in the extreme southern part of the State. There is no mention of salt water in the log of the 2,306-foot well at Atlantic City, although, except for the 2,350-foot well at Key West, Fla., that well is the deepest in the entire Atlantic Coastal Plain. Salt water has been reported at Lewes, Del.; Pocomoke, Md.; in Accomac and Northampton counties, on the eastern shore of Virginia; and in Mathews, Gloucester, Elizabeth City, Norfolk, and Princess Anne counties, on the western shore. In North Carolina salt water is known to have been found by deep wells in Hyde, New Hanover, Columbus, and Brunswick counties, and was presumably found in Pasquotank, Tyrrell, Beaufort, and Craven counties. In South Carolina it was found in Beaufort and Charleston counties. In Georgia, though it is altogether likely that salt water has been struck, the wells have not been reported.

RELATIONS OF SALT-WATER BEDS.

It is noteworthy that except in North Carolina all the salt-water areas are near the sea or in low land bordering the seacoast. The North Carolina wells are in a stretch of country that is nowhere 50 feet above tide; much of it has an elevation of less than 20 feet. The salt-water wells of Virginia, Maryland, Delaware, and New Jersey are in areas having elevations of less than 25 feet.

Although at probably all the wells some fresh water was found above the salt, at but four localities—Wildwood, N. J., Pocomoke, Md., Chisholm Island, S. C., and Charleston, S. C.—has fresher or decidedly less saline water been found below salt; at Crisfield, Md., waters containing but 136 parts of chlorine per million lie 770 feet below waters containing 291 parts, but neither of these is a "salt" water according to the definition on page 77. At one locality, Wildwood, N. J., flows of fresh and salt water were found to alternate to a depth of nearly 1,200 feet, but at five localities where wells have been sunk with care and different flows tested—Lewes, Del., Fort Monroe and Norfolk (Moores Bridges), Va., and Wilmington and Fort Caswell, N.C.—no fresh water has been found with increase in depth, though at the well in Hilton Park, Wilmington, the flow at 1,020 feet is a little less salty than the one above. From the Elizabeth City County wells it is safe to assume that the deep wells in eastern Gloucester County, Va., would not find fresh water at greater depth.

A comparison of the data in the table shows that salinity bears no apparent relation to the depth of beds below surface or to their age, and it is doubtful if the saline areas bear any relation to the very

slight folds that exist in the Coastal Plain. Not one of the areas is like those reported from Alabama, where natural gas in associated with the flows. At some of the Atlantic Coastal Plain areas enough sulphureted hydrogen is given off to cause a decided "sulphur" odor, but at others no such odor is perceptible. The Coastal Plain wells have but one feature in common—location near a large body of salt water or in low land.

CAUSES OF SALINITY.

Sea water.—The first suggestion that occurs to anyone seeking a reason for salt flows is that the beds yielding them were marine deposits and that the sea water imprisoned within the sediments has never been replaced by fresh water. One objection to this view is that though most of the flows cited in the table come from marine beds, the Potomac group, presumably of fresh-water origin, yielded salt water at Fort Monroe throughout a section of over 800 feet. Another objection is that the salt artesian waters do not resemble sea water in composition, as the following analyses show:

Analyses of sea water and water from salt wells.

[Parts per million.]

	Sea water.[a]	Severn, Va.[b]	Fort Caswell, N. C.[c]	Charleston, S. C.[d]
Total solids	35,000	5,008	17,634	3,679
Silica (SiO_2)		39	5.6	45
Iron (Fe)		4.9	8.4	
Calcium (Ca)	419	46	598	21
Magnesium (Mg)	1,304	26	40	33
Sodium (Na)	10,707	1,826	6,440	1,157
Potassium (K)	387		9	71
Carbonate radicle (Co_3)	72	0	0	299
Bicarbonate radicle (HCO_3)		628	868	
Sulphate radicle (SO_4)	2,693	216	26	175
Chlorine	19,352	2,500	10,400	1,489

[a] Dittmar.
[b] R. B. Dole, analyst.
[c] J. R. Evans, analyst.
[d] Shepard Laboratory, analyst.

Too much weight may be given to the differences shown above between sea water and the water of the salt wells if the possibility of chemical reactions which might result in the precipitation of lime and magnesium salts from the buried sea water is disregarded, but at least they indicate that the present flows are not unchanged sea water. In fact, it would be strange if they were. Successive elevations and depressions of the land are recorded in the geology of the Coastal Plain. In periods of elevation underground circulation has been quickened and fresh water has gradually leached marine deposits and forced out any original sea water. In periods of depression the outcrops of fresh-water bearing beds have been saturated by sea water and blanketed by marine deposits. Another period of elevation has started fresh water down the dip, displacing sea water,

leaching marine deposits, and forcing the salt but freshening solutions into the underlying beds. Thus, a bed that originally was a fresh-water deposit may have been repeatedly invaded by salt water from above and the present salinity of the water in a particular area is to be regarded as connected with the last invasion of salt water rather than with any sea water imprisoned in the beds at the time of deposition.

Slow circulation.—Differences in mineralization due to differences in the origin or the composition of a particular bed, or of underlying beds, may be modified by differences in the ease of circulation of water through them. As the members of the Coastal Plain formations tend to lenticular form and varied texture, water that enters an artesian bed does not progress seaward along a straight line down the dip, but may cut across beds through joint cracks, rising or sinking on the way, may follow a zigzag course through connecting lenses of sand, and conceivably may flow up the dip for short stretches. As the inclination of most of the formations is slight, and as most of the waters do not run through open channels for any great distance but more through capillary spaces between grains of sand, their passage is slow and they constantly lose head. In their journey they dissolve various mineral substances, the work of solution at any particular point being determined by temperature, pressure, and substances already in solution. An increase in the proportion of clay in a certain sand bed may check the seaward movement, or the bed may pinch out altogether, ponding the water landward. This ponded water, already more or less mineralized, may dissolve the minerals of the bed in which it lies and thus become more mineralized than water at an equal distance from the outcrop but having a freer passage toward the sea. On the other hand, the fineness of a bed at the precise spot at which it is tapped by a well is not necessarily significant, for the outlet from coarse beds may be obstructed as readily as that from fine beds. Some of the most saline flows in Virginia come from gravels or coarse sands.

To recapitulate, the salinity of a flow may be derived from sea water or from water that has leached marine deposits and sunk down the dip, following an elevation of the land. The location of salt-water areas is determined by original or imposed salinity and subsequent imperfect circulation. Salt-water beds freshen as circulation down the dip is established; they are found near the coast chiefly because the percolating meteoric waters have not been able to complete their work farther since the last invasion of the sea. However, wells less than 200 feet deep, situated on islands or on the shores of a wide body of salt water, may be subject to a slight but effective seepage of sea water through the beds overlying the sand, particularly if they are heavily pumped.

In comparing places miles apart account must be taken of differences in initial head caused by differing elevation of the outcrops of the porous beds.

LATERAL CHANGE IN SALINITY.

Freshening of areas.—Owing to the tendency to lenticular form and the varying texture of the beds of the Coastal Plain, it is sometimes impossible to trace a particular water horizon more than a few miles or to determine the exact correspondence of a salt-water bed with a bed some miles distant yielding fresh water. The measure of freshening from a salt-water area in a series of beds can, however, be determined. At some places there is notable variation in saltness within a few miles. At others the change is more gradual. At Charleston, S. C., as shown by C. W. Shepard, jr.,[a] the salt-water area is rather sharply defined landward. The water from a 425-foot well at Chisholm's Mill, three-fourths of a mile from the city hall, contained 1,489 parts of chlorine per million and that from a 375-foot well of the Edisto Phosphate Company, 4 miles away, contained only 849 parts.

A similar instance of westward freshening is furnished by wells near Norfolk, Va. A bed at 738 feet in the Norfolk waterworks well yielded water containing 1,165 parts of chlorine per million; the 616-foot Norfolk and Western Railway well at Lambert Point, 6 miles farther west, yielded water containing only 351 parts. In Gloucester County, Va., the flow of a 594-foot well at Gloucester Point contains 300 parts per million of chlorine; the flow of a 610-foot well 4½ miles to the northeast contains 1,400 parts, and that of a 585-foot well 6½ miles to the northeast contains 2,500 parts. At Wilmington, N. C., the deep well at Hilton Park flows, presumably from a depth of 1,020 feet, water containing 7,400 parts of chlorine per million; and the deep well at Fort Caswell at the mouth of Cape Fear River, 25 miles farther south, flows from a depth of 1,440 feet water carrying 10,400 parts. All the above comparisons are weakened by the differences between the time of drilling and that of making analyses—that is, they take no account of possible freshening through flowing.

Freshening of individual wells.—The quickening of circulation that follows the tapping of a water bed by a well must ultimately result in freshening a salt flow. Fuller,[b] who suggests that such salt wells be allowed to flow freely in the hope of their finally yielding fresh water, mentions instances of improvement near Wilmington, two permanent and two temporary. The temporarily bettered wells

[a] Artesian wells, Municipal report of the city of Charleston, 1881.

[b] Fuller, M. L., Instances of the improvement of water in wells: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, p. 96.

became fresh after heavy pumping for half an hour to an hour, and become salty again when disused. They seem to be in a distinct class, and their peculiar behavior may perhaps be accounted for by imperfect casing and by the drill having struck two flows, one fresh and the other salt.

No analyses of the permanently improved flows were made just after the completion of the wells, so the exact amount and rate of freshening can not be determined. Analyses are the only safe guides in comparison, taste being too uncertain, and analyses of Coastal Plain flows for a term of years are few. They are available, however, for the Norfolk and Western Railway well at Lambert Point and the 1,250-foot well on Wentworth street, Charleston.

In the Lambert Point well the water contains less than 500 parts of chlorine per million and is therefore not a salt water, as previously defined. The analyses are as follows:

Analyses of water from well of Norfolk and Western Railway, Lambert Point, Va.

[Parts per million.]

	1.	2.	3.	4.
Total solids	1,093	1,094	.....	1,128
Silica (SiO_2)	10.0	11.4	11.0	6.0
Oxides of iron and aluminum ($Fe_2O_3+Al_2O_3$)	.91	1.37	2.6	1.9
Calcium (Ca)	5.0	5.4	4.8	5.1
Magnesium (Mg)	1.7	2.8	2.7	3.3
Sodium (Na)	415.0	439.0	434.0	437.0
Potassium (K)	21.0			
Sulphate radicle (SO_4)	43.0	44.0	43.0	45.0
Carbonate radicle (CO_3)	245.0	314.0	.....	312.0
Bicarbonate radicle (HCO_3)	.....	.....	617.0	.....
Chlorine (Cl)	351.0	290.0	293.0	290.0

1. Shepard Laboratory, analyst, 1891.
2. Norfolk and Western Railway Company, analyst, 1899.
3. Dearborn Drug and Chemical Company, analyst, 1907.
4. Norfolk and Western Railway Company, analyst, 1909.

Allowance being made for differences in analytical methods, the rate of freshening shown is indefinite and is so slight that it would not pay to sink a well near by in the hope of ultimately getting fresh water from it.

Comparisons can be made of the Charleston waters in but one well, the 1,250-foot well on Wentworth street. An average of analyses made in 1868 shows 776 parts of chlorine per million. A field test made in 1907 showed over 900 parts. If there is no break in the casing, the salinity has increased.

SUMMARY.

Areas in which salt water may be found by deep drilling are more numerous than has been supposed.

These areas are in low ground and the greater part are near the ocean or some large body of salt water.

There is no foundation for the opinion that fresh water can always be found below salt or can be found in a particular formation where salt water has been found in an overlying formation. The probability of finding fresh water below salt is a problem for each area, and inferences based on work in one area may be utterly misleading in another.

As salt-water beds freshen up the dip and as the seaward limits of most of them are unknown, the prospect of finding fresh water is better to the west rather than to the east of any particular salt-water well.

Salt flows are not peculiar to any one horizon and have no known relation to the geologic age of a deposit.

Salt flows are due to various causes; chiefly (1) to the leaching of marine deposits and (2) to the penetration of sea water or the leaching of marine beds into underlying deposits. Differences in rate of circulation caused by differences in initial heads, loss of porosity, or pinching out of water-bearing beds will account for some differences in mineralization.

Although a renewal of active circulation through a well must result ultimately in freshening the flow, so little is known of the rate of freshening that drilling wells in a salt area in the hope of getting fresh water is not advisable unless rapid freshening in a particular locality has been proved.

MAGNETIC WELLS.

By Myron L. Fuller.

INTRODUCTION.

It is a fact well known to deep-well drillers that the casings of many deep borings are more or less magnetic and will attract and hold to the pipe small iron or steel objects coming within their sphere of influence. Furthermore, many newspapers and occasionally engineering and other magazines have printed statements ascribing magnetic properties to the water itself, and it is not unusual for spring waters to be exploited as "magnetic." A large number of these waters were investigated, and in most of them no magnetism whatever was found; in others the only magnetism was that shown by the well casings. The object of the present paper is to put on record some observations on magnetic wells and so-called magnetic spring waters, and to suggest certain lines of experiment which will afford more reliable data as to the phenomena observed.

PHENOMENA.

MAGNETISM OF CASINGS.

Occurrence.—During or after the drilling of wells it is frequently found that the casing has become magnetized. This discovery is usually made through the adherence to the pipe of nails or other small objects brought near it. The phenomenon is exhibited principally in the attraction of small objects to the pipe, the clinging of steel tapes and wires to the casing when measuring the depth of wells, the attraction of steel cables to the casing in drilling, and the attraction of the magnetic needle when in the vicinity of the casing.

As a rule, the magnetism of the casing is only sufficient to hold small nails or similar objects, but occasionally it is much stronger, and will hold nuts, bolts, and spikes against the pipe, and it is reported that even metal dippers and other large objects have been likewise held. The casing of a well at Wheeling, W. Va., tested by Prof. William Hallock for the United States Geological Survey, was 4,500 feet in length and is said to have had sufficient magnetism to hold a wrench.

In the measurement of certain wells the magnetism of the casing presents an important obstacle. A. C. Lane has found that the cling

of the steel line used in lowering thermometers into deep wells is very considerable. He says[a] that in the well at Grayling, Mich., it required a man's full strength to start 2,600 feet of steel tape, although the weight of the tape itself was not over 25 pounds. Again, he reports that in a well at Cheboygan the magnetic drag on the tape used in measuring was so great, according to Mr. Rust, the driller, that it was impossible to tell when the 20-pound weight had reached the bottom.

As would naturally be expected, the needle of a compass is strongly attracted by a magnetic casing, being deflected toward the well in all positions for distances varying with the strength of the magnetism.

Relation to depth of well.—The relation between the length of the casing and the strength of the magnetism is not constant. According to Lane,[b] however, the larger and deeper holes are in general more magnetic than the shallower ones. This would probably always be true if all other conditions were uniform, which is generally not the case. In reality the magnetism of the casings in many of the deeper wells is feeble, whereas in some shallow wells, as in the 90-foot drift well of the Moline Plow Company at Madison, Wis., examined by A. R. Schultz, of the Geological Survey, the magnetic force was sufficient to hold a hammer and a heavy wrench against the pipe.

Relation to location.—The data bearing on the distribution of magnetic wells are too few to permit other than broad generalizations. Only one such well has come to the attention of the writer in the coastal plain regions of the Atlantic or Gulf States, and only a few have been reported from the Central States. In Pennsylvania, however, the drillers report that magnetic casings are common, the development occasionally being rather strong. Magnetic wells are especially numerous in Michigan, Wisconsin, and Minnesota. About a dozen came to the attention of Mr. Schultz in a season's investigation in Wisconsin, and it is probable that there are hundreds of others in which the magnetism exists but has not been noticed.

Relation to materials penetrated.—Information regarding the relation of the magnetism of casings to the materials in which the well is drilled is very fragmentary. Wells in Carboniferous sandstones, shales, and limestones and in Upper Devonian shales are magnetic in Pennsylvania, Michigan, and elsewhere, and wells in drift are not uncommonly magnetic in the north-central States. No reliable reports of magnetic wells in granite have been received, but it is believed that they would be as common or even more common than those in the rocks just mentioned were it not that their casing is carried only a few feet into the rock. One magnetic well is known in the Coastal Plain, and there is no reason why others should not be found. For the reasons outlined in the paragraphs on the causes of

[a] Fourth Report Michigan Acad. Sci., 1904, pp. 166–167. [b] Loc. cit.

the phenomena, magnetic wells are most numerous and powerful in the harder rocks, in which the casings are carried to the bottom, and least common in soft, unconsolidated deposits. Wells in drift or other deposits carrying magnetic sands or bowlders, however, would be exceptions to this rule. Theoretically the magnetism should be greatest in wells in granites and quartzites, and should decrease more or less progressively through schists and other soft crystalline rocks, limestones, sandstones, slates, shales, clays, etc.

Loss of magnetism.—The testimony of drillers seems to be unanimous that the magnetism decreases with the lapse of time and in many wells disappears in a few years. One of the best examples is afforded by a well sunk near Grand Valley, Pa., in 1905. At that time it was found by the driller, Josiah G. Winger, to be strongly magnetic. On repeating the test a few months later, at the Survey's request, he found that the magnetism had entirely disappeared. A considerable number of so-called magnetic wells have been tested by the writer and other members of the Survey, but the magnetism was not detected, apparently having disappeared since the completion of the wells.

MAGNETISM OF DRILLS.

Magnetism of the drill is less commonly reported than magnetism of the casings, although well drillers in the Pennsylvania oil and gas fields say that it is very common. Mr. Schultz found that in the well of the Moline Plow Company at Madison, Wis., the drill, though strongly magnetic, was much less so than the casing, which held a hammer and iron wrench, the largest objects held by the drill being nails. It will probably be found on testing that magnetic drills are very common, but that the magnetism is as a rule not so strongly developed as in casings.

MAGNETISM OF WATER.

In the course of his field work the writer has visited a number of wells whose water is alleged to produce magnetism in iron objects immersed in them, and waters from several "magnetic" springs (in reality deep wells) are on the market. So persistent have been the reports of such waters that, notwithstanding their apparent inherent improbability, the writer has taken every occasion to make careful tests in the field.

The waters of most of the so-called magnetic springs emerge from pipes, and are thus artesian wells rather than true springs. In these, as well as in natural springs, the waters are generally strongly chalybeate and deposit considerable amounts of iron oxide, which doubtless suggested the tests for magnetism. The phenomena reported consist in the magnetization of needles, knife blades, nails, etc., immersed in the water, both at the source and at a distance, and in the deflection of the magnetic needle in its vicinity.

To test the matter, two members of the United States Geological Survey visited one of these springs (the Cartersburg Spring (well) near Indianapolis, Ind.) at different times and carefully tested the steel (1) before approaching the "spring," (2) immediately before placing the knife in the water held in the glass jar, and (3) after allowing the knife to stand in water for five minutes at various distances from 5 to 150 feet from "spring." No magnetism whatever was produced by the water and even the casing was found to be nonmagnetic.

The waters of this "spring" or well are strongly chalybeate and, according to J. N. Hurty, chemist for the Big Four Railroad, deposit magnetic oxide of iron.

Similar tests made by the writer and others on alleged magnetic wells in Ohio and Minnesota gave the same negative results.

Objects were reported to have been magnetized by the water in the Moline well at Madison, Wis., but investigation brought out the fact that the water had been collected in a metallic dipper which possibly came into contact with the magnetized casing and was magnetized by it, and which in turn magnetized the iron placed in it. Tests by Mr. Schultz showed that unmagnetized steel or iron left for an hour in the water in nonmagnetic vessels showed no magnetic properties, nor did iron held in the water in the well when carefully shielded from the casing. J. G. Winger made a careful test of the well near Grand Valley, Pa., and found that although the casing was strongly magnetic the water showed no magnetic phenomena. In fact, there is at present no evidence that magnetism can be imparted by water to objects of iron or steel.

It is believed that the errors in the observations of those who suppose they discover magnetism in water arise mainly from three causes. Although relatively few people are aware of it, many pocketknives are more or less magnetized, and it is not safe to assume without testing that a particular knife is nonmagnetic before it is placed in the water. Another cause of misinterpretation arises from the fact, also not generally known, that many well casings are magnetized, and that the magnetism attributed to the water is really due to the presence of this magnetic body in the vicinity of the knife tested. Still another cause of error lies in the fact that the knife is not wiped after being taken from the water and that the surface tension of the film of water on the damp blade may pick up a needle.

The following simple procedure, requiring no instruments, would go far toward settling the question of magnetism in natural waters. Take several pieces of steel and a number of needles which have been tested and found to be unmagnetized to a point 200 or 300 feet from the well or spring to be investigated, and after again testing steel and

needles leave them, together with any other iron or steel articles about the person, at this point. Proceed to the well or spring and fill a large glass vessel with the water, and return with it to the steel and needles. Test these again and then place one of the pieces in the water in the glass vessel, leaving it there for five minutes. On removing the steel dry it and test it with a needle for magnetism. The experiment, if the magnetism is in any way connected with chemical changes in the water such as those depending on the passing off of the CO_2, should be made as quickly as possible. If found magnetic the steel and needle should be laid aside, care being taken that they do not come near the remaining pieces. If the water taken from the spring in a glass vessel shows no magnetism it may be desirable to test the spring itself for magnetism. To do this a previously tested piece of steel should be taken to the spring and left in the water for five minutes or more, after which it should be removed, dried, carried back to the base of operations, and again tested. If found magnetic the experiment should be repeated with a steel object left just outside the water limit at the spring. By a number of such tests the source of the magnetism, if any is present, can probably be located.

Of instrumental tests, that with the common compass is the easiest to make and consists in determining the distance from the well at which the needle is first found to be affected, and the distance at which it will point directly toward the well from the east or the west.

CAUSES OF MAGNETISM OF CASINGS.

The magnetism of well casings has been attributed to a number of causes, which include (1) the striking of magnetic bowlders, (2) the penetration of magnetite-bearing sands or rocks, (3) electric currents in the water, (4) magnetic material in suspension in the water, (5) chemical action of the water, (6) the interception of the magnetic lines of force in the earth, and (7) the production of induced magnetism by the motion of a magnetized drill.

Magnetic bowlders.—If magnetic bowlders were encountered by a drill or casing it is conceivable that they might impart magnetism, but although magnetite is common in bowlders of the glacial drift and is capable of being attracted by a magnet, it does not itself possess the property of magnetism, and it is difficult to see how a casing or drill striking such materials could become magnetic.

Magnetite sands or rock.—Many varieties of the crystalline rocks contain magnetite in fine particles, and when reduced by disintegration and decay, or by wave action, yield sands that abound in magnetite grains. These grains may be scattered through the drift or concentrated into thin beds or layers in stratified rocks. A well drilled in crystalline rocks, especially in the basic types, will generally encounter more or less crystalline magnetite, and even wells in

drift and in stratified materials, both consolidated and unconsolidated, may encounter the included magnetite particles. The objection to this explanation of the derivation of magnetism is the same as to that of the magnetic bowlders, namely, that though the magnetite is attracted by a magnet it does not itself exhibit polarity and it probably can not induce magnetism in iron coming into contact with it.

Electric currents in water.—It is a matter of frequent observation that in cities electric currents entering the ground from trolley rails and other sources seek the water conduits, the iron casings being gradually destroyed by the process of electrolysis. Similarly it has been assumed that earth currents of electricity tend to follow the underground water conduits, and, although relatively weak, may impart magnetism to the casings through which the water is flowing. If magnetic wells were always flowing wells this might explain the phenomena, but in reality many magnetic wells, especially in the oil regions, including some even several thousand feet in depth, contain no water at all and contain oil only at the bottom.

Magnetic material in suspension in water.—Magnetic material held in suspension in water might be thought competent to magnetize iron or steel, but in reality particles in suspension lack the orientation necessary to induce magnetism. Moreover, there is no known source of such particles. Magnetite sand might be drawn in, but, as previously stated, can not induce magnetism. One chemist has asserted that the "magnetic" oxide may be precipitated in natural waters on standing, but even if this is true the precipitate does not possess magnetic properties.

Chemical action of water.—In chalybeate waters galvanic action is set up between brass or zinc well strainers and the iron casing, but there is no known means of producing the phenomena of magnetism in the iron by such a process. Besides, magnetism is found in wells not provided with strainers and independently of the quality of the water.

Induced magnetism from magnetic force of the earth.—As is well known, a steel body that remains for some time in one position may become distinctly magnetic owing to the polarization of its particles by the earth's magnetism. The strength of this action in wells should be proportional to the length of the casing, and as a matter of fact has been so found by William Richards, who has drilled many wells in Pennsylvania. On the other hand, some of the strongest magnetic wells yet noted are less than 100 feet in depth. The strongest arguments against such induced magnetism of the casings are (1) that the magnetism decreases rapidly after the completion of the well, and (2) that, according to Mr. Richards, pump tubes of equal length or longer than the casings do not become magnetic even when inclosed

within an outer magnetized tube. Moreover, as will be pointed out in the next paragraph, the relation of length of casing to strength of magnetism can be explained otherwise than by direct induction.

Induced magnetism from drill.—That casings are not commonly magnetized by direct induction is probably due to the immobility of their particles. With the drill, however, these conditions are different. Through its rise and fall sharp vibrations are produced which tend to facilitate the readjustment of its molecules and their orientation according to the direction of the earth magnetism at that point. In some wells the drill when inserted was known not to be magnetic, but became so after being used a short time, even where no casing had been introduced. As this occurs in rocks where the other enumerated possible causes are out of the question, it seems certain that the magnetism of the drill has resulted in some such way as is here outlined. When, after the drill is magnetized, it is repeatedly passed in the process of drilling up and down through the casing in the same position and direction of movement it gradually imparts its magnetism to the casing. The larger the casing and the deeper the hole the more pronounced is the phenomenon.

In driving wells the casing itself may become directly magnetized, as in some materials the casing is forced downward only with great difficulty and by means of heavy driving weights, which set up vibrations much the same as those of the drill, and which possibly induce more or less magnetism.

CONCLUSIONS.

The magnetism exhibited by well casings is independent of depth, many shallow wells showing it as strongly as the deeper ones; it is not a question of material, for it is found in wells in all classes of materials. It is not due to electric currents nor to magnetic particles in water, as it is shown in wells without water as well as those filled with it, and it is not due to induction by earth magnetism, as it soon disappears after the completion of the well and is not found in the pump tubes. The casing is usually magnetized only when the drill is worked inside of it, a fact which explains the general absence of the phenomenon in granite and other rock wells in which the casing is carried only to the rock. This also explains why it is most common in deep cased wells, such as those of the Pennsylvania oil fields. Observation seems to indicate that the drill is the first to become magnetized, the casing showing magnetization later. The strength of the magnetization seems to be proportional, other things being equal, to the hardness of the rock. The facts briefly stated lead the writer to the conclusion that the phenomena are induced by earth magnetism aided by the vibration of the drill or of the casing when it is sunk by percussion, which permits the readjustment of the polarized particles of the steel.

UNDERGROUND WATERS NEAR MANASSAS, VIRGINIA.

By Frederick G. Clapp.

LOCATION AND GEOLOGIC ENVIRONMENT.

Manassas lies within and about 1½ miles west of the eastern border of the belt of Triassic sandstones which crosses northern Virginia. East of this belt the rocks are metamorphic and schistose in nature, with much contorted dips, generally at a high angle. The line of demarcation between the two areas crosses Bull Run at the mouth of Russia Branch, on the line of the Southern Railway, and extends in a direction slightly west of south along the west slope of Signal Hill. West of Manassas the Triassic basin extends nearly 20 miles to the Bull Run Mountains.

In the vicinity of Manassas the Triassic rocks consist of red sandstones of varying degrees of coarseness, lying nearly flat, with dips where measured of about 12°. The rock is well exposed in a quarry about half a mile northeast of town, where it is being worked for building stone, and in several small excavations along a public road a short distance east of the quarry. Where the direction of the dip could be seen it was about due north. In general the stone is massive and consists of beds 1 foot to 8 feet thick, being thinnest near the surface. The owner of the quarry reports that water is not found in the bedding or joints. The beds are cut by fine joint cracks, but where noticed these generally extend across one or two beds only. No trap dikes are known in the vicinity of Manassas, but some are reported a few miles away.

WELLS.

Owing to the considerable number of drilled wells at Manassas, fair opportunity exists for obtaining information regarding the occurrence of water in these rocks. Probably the best-known well is that drilled in the summer of 1905 for a public water supply. This well is situated close to the Southern Railway on the eastern outskirts of the town, in a slight depression, around which the hills rise 15 or 20 feet higher. Data supplied by members of the

corporation of Manassas show that the well was drilled to a depth of 531 feet 8 inches, all but the last 6 or 7 feet through Triassic sandstone. At 525 feet a hard gray rock was struck, which continued to the bottom of the well and is supposed to be the metamorphic or crystalline rock that underlies the Triassic area. This well has a diameter of 8 inches to a depth of 200 feet from the surface, below which it is only 6 inches. It is reported to be cased to a depth of 180 feet. Two water-bearing beds are reported at depths of 210 and 487 feet, the deeper one supplying the greater amount of water. When the well was completed the water stood 58 feet from the surface. A 12 by 36 inch steam head pump was installed and a test of the well made, variously reported as lasting from six to ten hours, during which the well was pumped continuously. It is said to have yielded at least 120 gallons of water a minute, that being the full capacity of the pump. On account of lack of funds this well has never been used, but it is protected by a cement curb and housed over. Some persons have supposed that as this well is situated in a depression the water is liable to contamination, but if the casing extends to 180 feet, as reported, there is probably little danger.

On the Portner estate, on the northern edge of town, are half a dozen or more drilled wells, the deepest of which is 333 feet deep. The principal water is reported to occur in a coarse sandstone 220 feet from the surface. When this bed was reached the water, which had previously stood 24 feet from the surface, fell to 70 feet below the surface, where it remained, being unaffected by subsequent pumping. This well is pumped by a windmill and supplies enough water to maintain two fish ponds covering half an acre or more and to supply a bathing tank.

A few hundred feet to the north, near Mr. Portner's house, are two more wells about 100 feet apart. They are reported as being 215 feet and about 300 feet deep. They were connected by exploding a heavy charge of nitroglycerine in the bottom of one of them, establishing free communication for the water and permitting both wells to be pumped from one. A steam pump raises the water to a tank about 50 feet above the ground. These wells supply plenty of water for use of the house and stables. The water in the 215-foot well is said to have stood 60 feet from the surface and the principal supply to have come from a depth of about 200 feet.

A quarter of a mile or more still farther north, at Mr. Portner's stock farm, are two more wells. Both are said to be over 200 feet in depth and are pumped by a windmill. The water supplies 135 head of cattle, 20 horses, and 15 men, besides being used for cooling milk. These wells seem to show that there is plenty of water in the sandstones, if favorable localities happen to be found.

Mr. Prescott has a well said by him to be 200 feet in depth, in which the water stood 68 feet from the surface. The capacity of this well was only 8½ gallons a minute, but this is considered a good amount in that region, as it is sufficient for all domestic and ordinary farm purposes. Generally wells of moderate yield are tested with the sand pump.

A few hundred feet west of the Portner estate, on the road to Sodby Spring, are 3 deep wells, on the G. C. Round, Taylor, and Lipscomb properties. They are 145, 115, and 140 feet deep, respectively, and all yield water enough for domestic purposes. Mr. Taylor reports 10 gallons a minute from his well and 20 gallons a minute from the Lipscomb well. The following is a record of the Taylor well, as reported by the owner:

Record of Taylor's well, Manassas, Va.

	Thickness.	Depth.
	Feet.	*Feet.*
Soil, etc.	8	8
Slate	2	10
Brownstone	30	40
Sandstone, gray	50	90
Coal	1+	91+
Sandstone, gray		

The water is reported to occur in a coarse sandstone 1 or 2 feet thick at the bottom of the well, and the same stratum is supposed to furnish the water in the Lipscomb well, on the lot next to the north. This water has been analyzed by the Bureau of Chemistry of the United States Department of Agriculture.

South of Manassas, about half a mile from the railroad station, is a well 102 feet deep on the W. H. Morann place. This well procures water from a coarse bed 100 feet from the surface and is piped to supply four houses in the vicinity. In dry weather this well has been utilized to the full capacity of the pump and has never given out.

According to reports of the drillers and owners no well drilled in the Triassic area in the vicinity of Manassas has failed to find water within a depth of 100 to 200 feet, although some of them yield only a few gallons. So far as can be judged by reports, the water occurs at no particular horizon, although some wells near together seem to have a water horizon in common. The water generally occurs in a coarse bed of sandstone. In many wells near town the drillers report a "grindstone rock," which is said to average 20 feet in thickness and to be irregular in occurrence. It may be a dike, but this is very doubtful. "Flint rock," perhaps a hard limestone, is frequently reported. In quality the water varies considerably, both hard and soft water being found. It is commonly believed that the water is harder in the lower strata than in the upper, and softer at the

east end of town than at the west end; for this reason the corporation well was located at the east end.

A rather interesting well is that of Libeau Brothers, situated on the southern border of Manassas. This is a dug well 75 feet deep and 5 feet in diameter at the surface, but increasing downward to 19 feet at the bottom. A large supply of water, which filled the well within 6 or 7 feet of the surface, was found in a bed of very soft sandstone near the bottom. As the well stands on rather low ground, it is probable that some of this is surface water.

Few data are available regarding water in the rocks outside the Triassic area. All the information at hand is derived from observations on Signal Hill, just east of the contact. This hill is about 2 miles long and is surrounded by numerous springs, which some persons have supposed to be of deep-seated origin, but their volume is so small that they are probably all derived from the rainfall on the hill. Mr. Dickens has a well 62 feet in depth, in which water stands 20 feet from the surface. It is reported to have a capacity of 6 gallons a minute.

WATER SUPPLY OF MANASSAS.

At present practically all the well-to-do families in Manassas have satisfactory deep wells of their own, but for those who have not and for use in case of fire a public supply is needed.

The population of Manassas in 1900 was 817, but since that time it has increased slightly. If the present population is 1,000, and 60 gallons a day per capita is the maximum amount of water which would probably be consumed, 60,000 gallons ought to be sufficient for domestic purposes alone. The quantity of water necessary for fire protection must, of course, be added to the 60,000 gallons. Of course it is important to consider the need resulting from probable increase in population, but this will probably be offset for some time by the number of persons who have deep-well supplies of their own.

To provide the necessary water the corporation well, mentioned above, was drilled in 1905. If the test of this well is reliable, it will yield at least 120 gallons a minute, or 172,800 gallons a day, nearly three times the amount necessary for a population of 1,000. It seems very probable, however, that this capacity will not continue indefinitely, and if the supply is found inadequate another well will have to be drilled. Certain persons in the town have urged going to Signal Hill, or even to the Blue Ridge, for the town supply, but such an expense seems unnecessary. A well at a given spot is not certain to obtain water in quantity, as some wells furnish only a few gallons each, but if one well does not succeed another should be tried near by.

UTILIZATION OF THE UNDERFLOW NEAR ST. FRANCIS, KANSAS.

By Henry C. Wolff.

INTRODUCTION.

In August and September, 1908, investigations were carried on in the valley of South Fork of Republican River, near St. Francis, Cheyenne County, Kans., to determine the quantity of the underflow water and the possibility of recovering it for use in irrigation. This report embodies the chief facts obtained in the field work, together with suggestions for installing small pumping plants to recover the ground water.

Only a few years ago a large part of this valley formed one big cattle ranch, but at present it is divided into a number of ranches of moderate size, and increasing attention is being given to agriculture. About sixteen small irrigation ditches now take water from the river within 10 miles of St. Francis.

The soil of the bottom lands differs in quality from place to place. Certain areas are too sandy or too moist for cultivation and are better suited for pasture and hay lands, but the soil of a large part of the bottoms is excellent and is well suited to alfalfa and other crops. The best tracts of land lie between poorer sandy strips, an arrangement which is of great benefit in the development of the valley by irrigation, for it tends to make it practicable to irrigate all the better lands without overdrawing the sources of supply.

During times of light precipitation, high evaporation, and large draft on the ground water by growing vegetation the water plane often drops below the bed of the river and the stream runs dry. Thus the lack of river water for irrigation when it is most needed has led the farmers of the valley to consider the possibility of installing pumping plants.

The field work on which this report is based consisted of putting down test holes in the bottom lands through the alluvial deposit to shale, of making underflow velocity measurements, of collecting samples of sand and water for analyses, and of determining the slope of the water plane.

Acknowledgment must be made of the interest manifested and the assistance given by the people of St. Francis and vicinity. Not only did they aid the writer in every possible way, but through the Commercial Club of St. Francis they supplied all the necessary common labor required for the investigation.

THE UNDERFLOW.

WATER-BEARING MATERIAL.

South Fork of Republican River crosses the northwest corner of Kansas, flowing in a northeasterly direction. The river has cut down several hundred feet through the loess and Tertiary deposits of the high plains into the Pierre shale. In the bottoms this shale is covered to a depth of 15 to 20 feet with water-bearing sand and gravel derived from the disintegrated Tertiary deposits. The river flows for the most part upon this sand and gravel through a natural meandering channel formed by cutting away the upper portion of the deposit. Because of the shallowness of the gravels and the presence of the underlying impervious shale the stream has an unusually strong tendency to survive throughout the summer months. At places where the shale comes near the surface the stream bed is rarely quite dry, presenting a marked contrast to most of the streams in western Kansas, which disappear entirely at times during the summer. The river has many western tributaries that flow through canyon-like valleys, and these tributaries also show a strong tendency to maintain a summer flow. Similar draws entering the valley from the east are usually dry in summer and are not important feeders of the river.

Although the great part of the work was done near St. Francis, a few test holes were sunk along the valley for a distance of 10 miles above to 14 miles below that city. Within this distance the bottom lands range in width from half a mile to about 3 miles, this being also the approximate width of the alluvial deposits. The water-bearing material ranges in thickness from 10 to 25 feet and in most places consists of gravel that is adapted to well construction, containing enough coarse material to warrant the use of a well strainer having perforations as large as 1¼ inches long by three-sixteenths inch wide. Near the center of the valley the gravel is very clean and contains but little very fine material. Toward the edges of the valley the percentage of fine sand markedly increases and earthy material, probably washed down from the banks and uplands, becomes noticeable.

WATER PLANE.

Figure 23 shows the location of most of the test wells put down at St. Francis and of three private wells concerning which data were collected. The downward slope of the water plane at this point was found, from measurements of its elevation at stations Nos. 5, 4, and 12, to be 10.7 feet a mile to the northeast, as indicated by the arrow in the drawing.

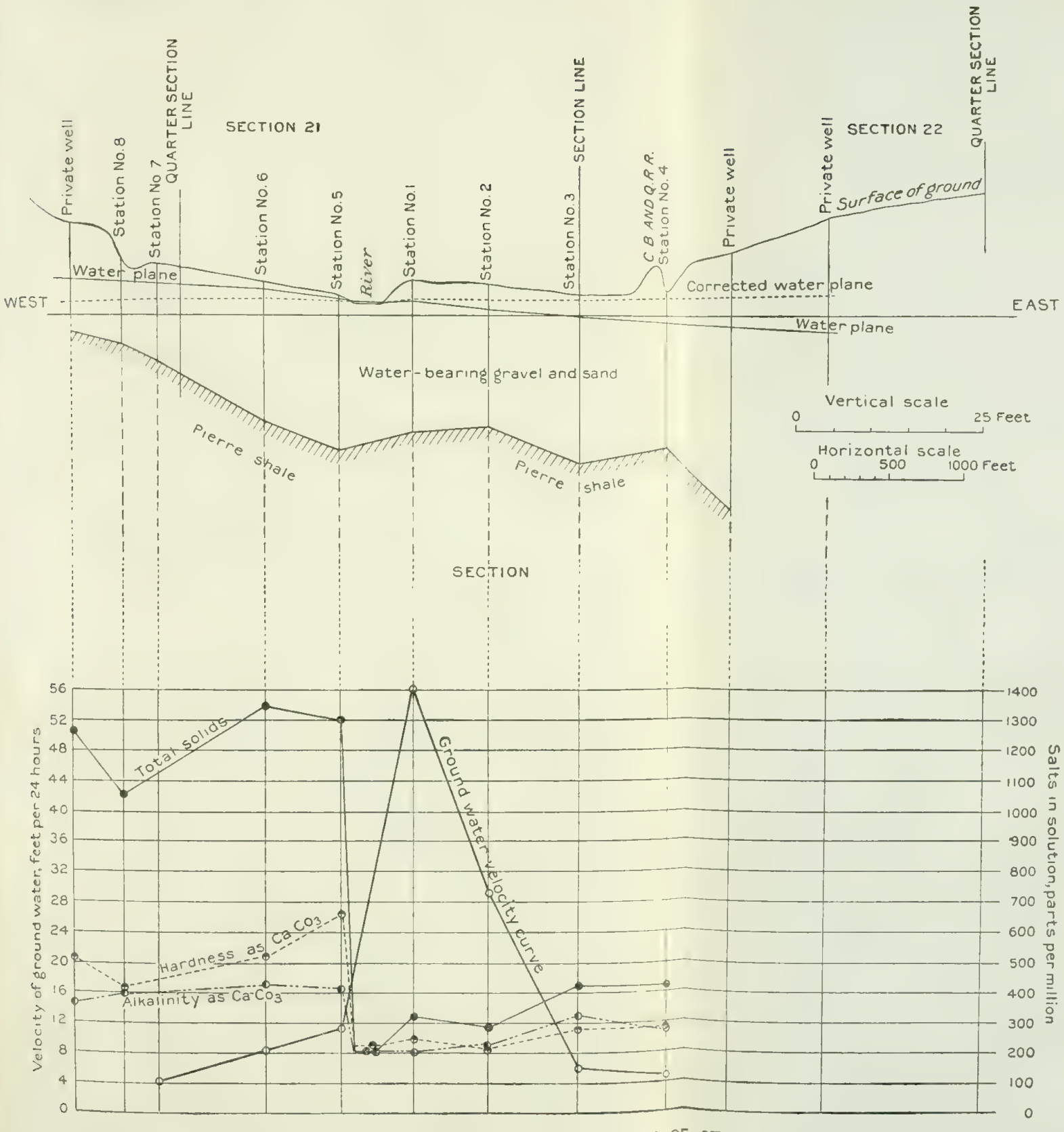
Plate II shows a cross section of the river valley along the east and west line of test wells at St. Francis. The vertical scale in this drawing is very greatly magnified, being 50 times that of the horizontal. The surface of the ground, the upper surface of the Pierre shale, the true water plane, and what is called the corrected water plane are all represented. The true water plane, shown by a full line, was determined by running levels to the test holes and private wells, and proved to have a decided downward slope from west to east. This slope was to be expected, for by referring to figure 23, the line of test wells from west to east is seen to be not normal to the channel, but to extend at an angle of about 45° to the general direction of the valley. Thus the wells at the east end of the line are farther down the river, and the water in them should stand lower than in the wells farther west. By correcting the measured elevations of the ground water along this line the dotted line in Plate II, marked "corrected water plane," is obtained. This line shows the position of the water plane along a line drawn at right angles to the direction of the valley, a position that is, in general, nearly level. At all points the movement of the underflow is down the valley, with no lateral components.

The upper part of figure 24 shows the location of a line of test wells 10 miles above St. Francis. The lower part is a cross section along the line of wells, showing the position of the shale and of the water plane. At this point the river has cut down nearly to the shale and has drained the water from the neighboring sands and gravel.

VELOCITY.

In figure 23 the arrows drawn from stations Nos. 1 to 7 represent in magnitude and direction the velocity of the underflow at these seven points. The numbers at the ends of the arrows represent the velocity in feet per twenty-four hours. The direction of the underflow follows very closely that of the river valley, which at this point is approximately 45° east of north.

In the lower part of Plate II the ground-water velocities are again represented graphically and may be read by the scale at the left, on which the vertical distance represents velocity in feet per twenty-four hours. The horizontal elements represent distances between test holes, as marked at the top of the drawing. From this



CROSS SECTION OF THE ARKANSAS VALLEY NORTH OF ST. FRANCIS, KANS.

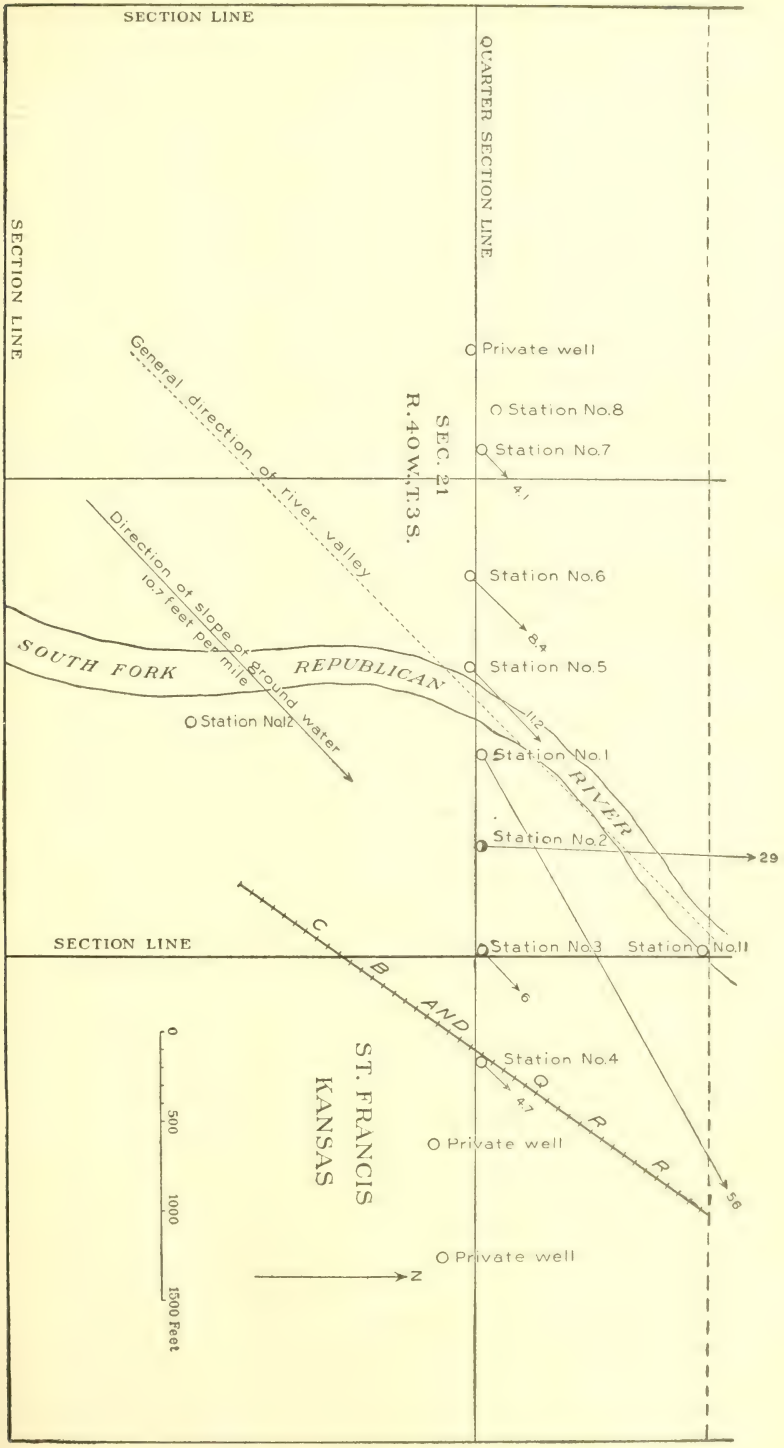


FIGURE 23.—Map showing location of test wells at St. Francis, Kans.

it will be seen that the velocity of the ground water drops from 56 feet per twenty-four hours near the center of the valley to about 4 feet per twenty-four hours at the edges of the bottom lands. This decrease is due principally to an increase of fine silt and claylike material in the water-bearing gravel from the center of the valley toward the edges of the bottom lands. Observations of the gravels taken from test holes sunk in the valley show that a similar variation occurs in any cross section of the bottom lands below St. Francis. This ground-water velocity curve represents in a general way the relative capacity of wells sunk along the line of the section. Therefore, other things being equal, a well sunk to obtain water for irrigation should be placed as near the center of the valley as practicable.

The average velocity of the underflow is 17 feet per twenty-four hours. If this rate of flow be divided by the slope of the water plane, expressed in feet per mile, the quotient is 1.6. This is the average velocity of the ground water that might be expected if the water plane had a slope of 1 foot to the mile. The corresponding factor for the underflow of the Arkansas River valley at Garden, Kans., is 1.1, which indicates that wells in the Republican River valley would have a somewhat greater capacity than those at Garden. The same indication is given by the general appearance of the water-bearing gravel, although no mechanical analyses have been made of the samples taken.

The area of the cross section of the water-bearing gravel at St. Francis, as shown in figure 24 and Plate II, is 71,500 square feet. This area, with an average normal underflow velocity of 12 feet per twenty-four hours and a porosity of one-third for the water-bearing material, would give a total flow of 3.3 cubic feet per second, or 1,485 gallons a minute, about the equivalent capacity of four 4-inch centrifugal pumps. These figures are given as an answer to the question often asked, "Would it not be feasible to construct a subsurface dam across the river to intercept the underflow and bring it to the surface?" Even if the cost of such a dam were neglected, a cost which alone puts it out of consideration, it would result in an inelastic system, yielding only 3.3 cubic feet per second continuously, and this yield could not be increased without using pumps.

REPLENISHMENT.

It is often asked (1) how it is possible for a well to yield any appreciable amount of water with so small an underflow, and (2) whether a large number of pumping plants simultaneously operating during the dry season would not exhaust the underflow in a few seasons.

In considering the first question it must be remembered that for slow velocities the flow is directly proportional to the hydraulic gradient, and that in the neighborhood of a pumped well this gradient is increased when the pump is in operation from a few feet per mile

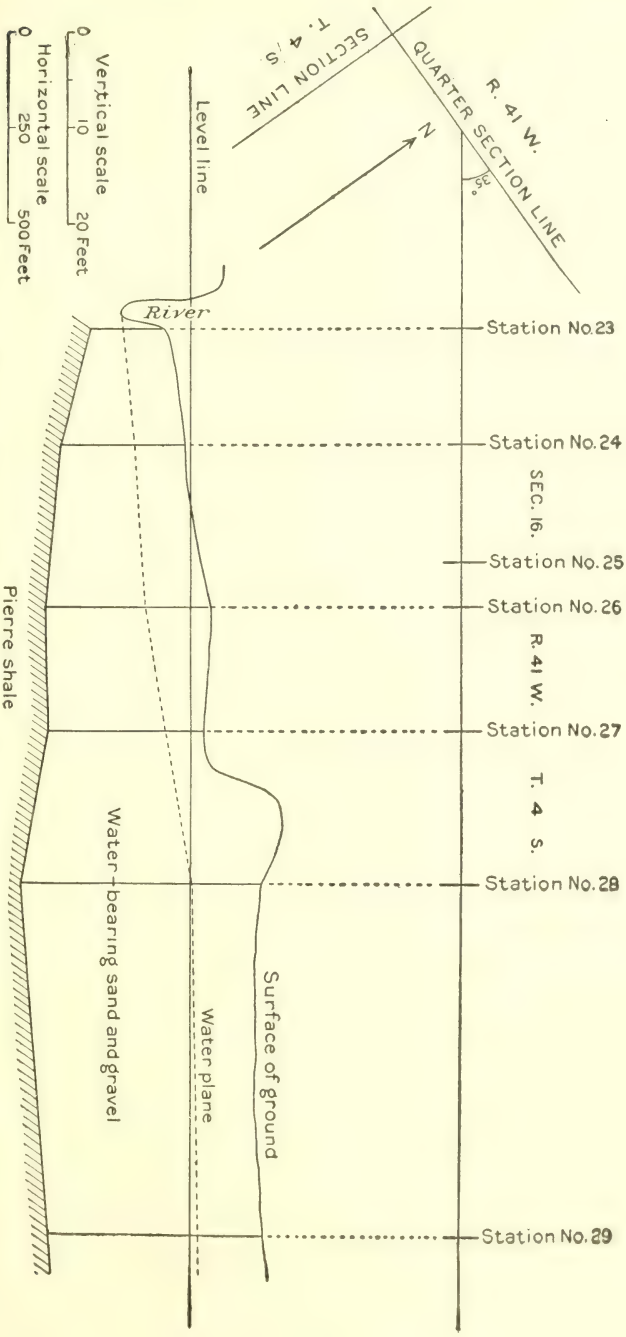


FIGURE 24.—Location of test holes 10 miles above St. Francis and cross section showing position of the shale and of the water plane.

to perhaps the same number of feet per yard. Figure 25 represents the depressions of the water plane in the neighborhood of a 15-inch well in the Arkansas River valley near Deerfield, Kans. Each curve represents the position of the water plane after seven hours continuous pumping, the pump being so gaged as to hold the drawdown of the water in the well pumped at 2.2, 4, 6.4, 8.6, and 11.7 feet below its normal position. The curves are replotted on logarithmic paper in figure 26, and here become straight lines, whose equation may be determined. This well was provided with an 8-foot strainer and under the heads named furnished, respectively, 31, 59, 94, 121, and 152 gallons a minute. These relations between yield and draw are plotted in figure 27, from which it will be seen that for drawdown of less than 7 feet the yield was directly proportional to the distance the water was lowered. Beyond this point the increase in yield for each additional foot of pressure grew smaller, as shown by

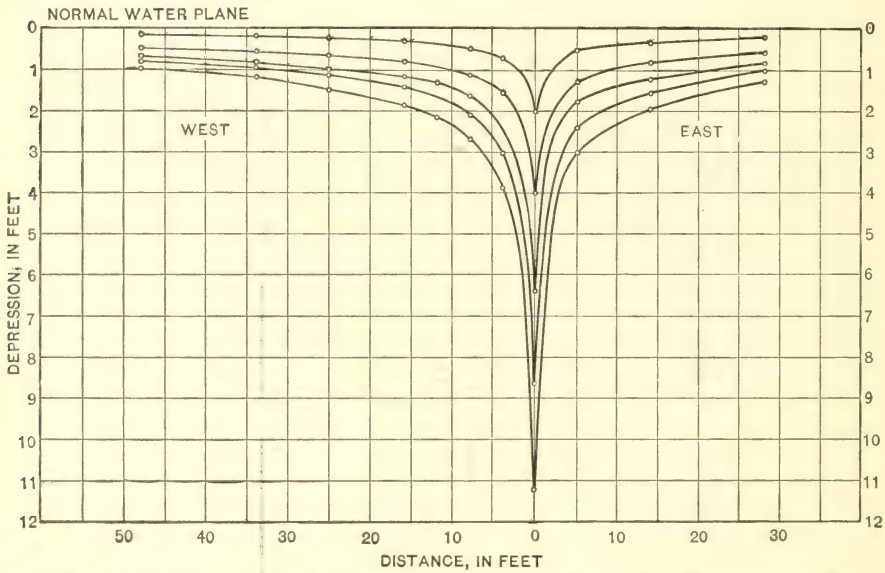


FIGURE 25.—Curves showing position of water plane near a 15-inch pumped well in the Arkansas River valley near Deerfield, Kans.

the bending of the curve above the straight line. The yield is therefore plentiful.

There need be no fear that the ground water will be exhausted in any number of seasons. Suppose that on each section or square mile of the bottom lands there are a number of plants pumping constantly night and day at the combined total rate of 1,000 gallons a minute for one hundred consecutive days; and suppose also that during this time there is no precipitation, that the river is perfectly dry, and that none of the water used for irrigation finds its way back to the underflow, so that there is no replenishment of the ground water; then the ground-water plane would be lowered about 2 feet. The

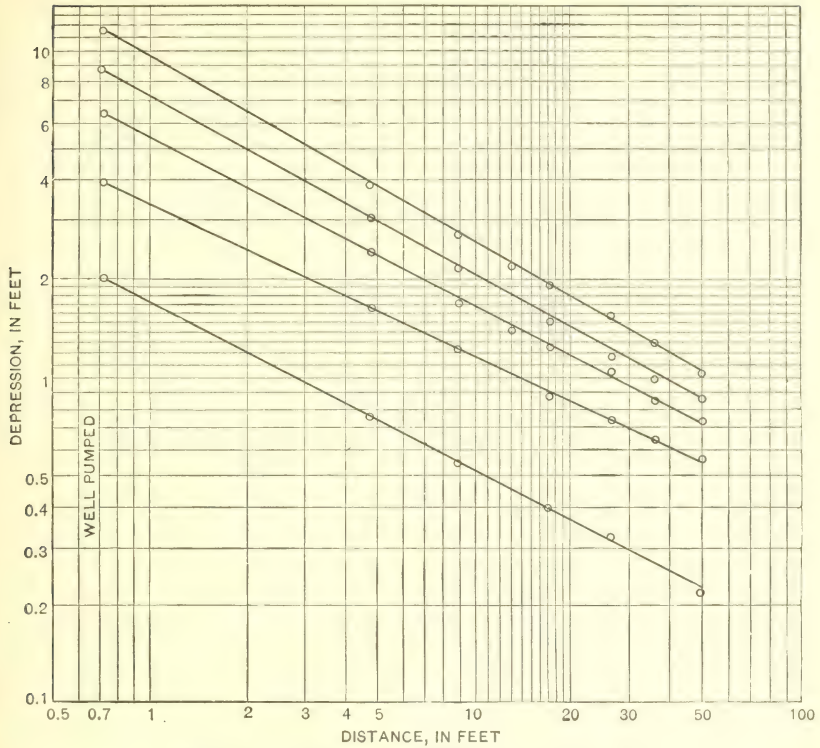


FIGURE 26.—Logarithmic representation of data in figure 25.

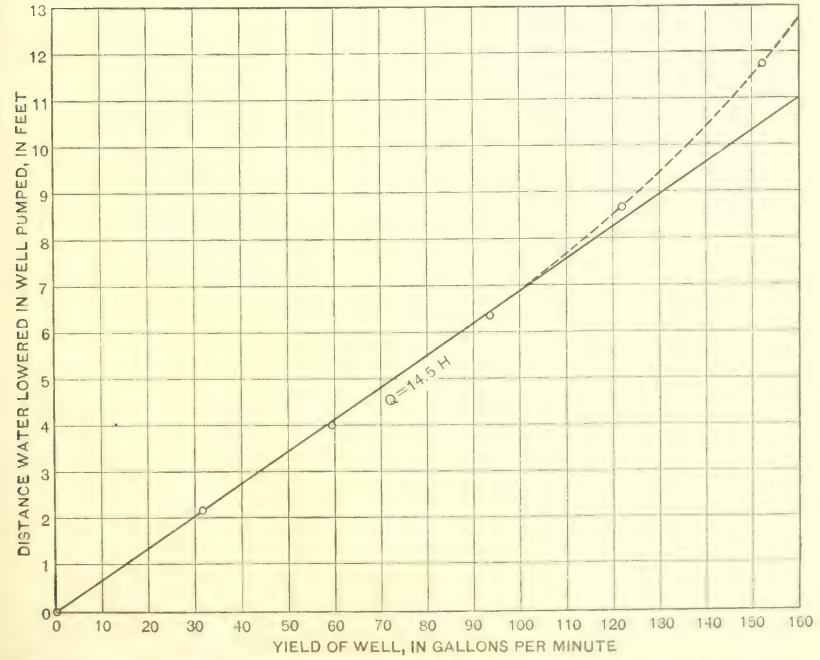


FIGURE 27.—Curve showing relation between yield and drawdown in a 15-inch well in the Arkansas River valley near Deerfield, Kans.

water thus recovered would irrigate two-thirds of each section to a depth of 1 foot. If the water plane were thus drawn down below the bed of the river, part, if not all, of the overflow passing St. Francis would not reach Benkelman but would join the underflow by sinking into the loose sandy bed of the river. The farther the ground water is lowered the faster will this transfer from overflow to underflow take place.

TABLE 1.—*Estimated discharge of South Fork of Republican River at Benkelman, Nebr., 1903–1906.*[a]

Month.	Discharge in second-feet.			Total (acre-feet).
	Maximum.	Minimum.	Mean.	
1903.				
May (20–31)	57	36	48	1,140
June	65	7	37	2,200
July	36	7	15	922
August	79	7	25	1,540
September (1–5 and 14–30)	22	7	15	655
October	50	7	39	2,400
November (1–20)	65	50	57	2,260
1904.				
March	102	31	60	3,690
April	66	6	21	1,260
May	255	47	92	5,680
June	397	47	132	7,850
July	115	5	39	2,420
August	89	11	24	1,480
September	47	5	13	774
October	115	31	57	3,540
November	66	47	59	3,530
1905.				
March (17–31)	249	96	159	4,730
April	300	52	141	8,390
May	137	52	100	6,150
June	283	21	68.6	4,080
July	152	5	35.4	2,180
August (1–13)	96	21	47.7	1,230
1906.				
April	317	73	129	7,680
May	215	52	99.3	6,110
June	52	0	90.3	5,370
July	183	0	10.9	670
August	0	0	0	0.0
September	0	0	0	0.0
October	61	0	21.8	1,340
November	61	36	48	2,860

[a] Water Supply Papers U. S. Geol. Survey Nos. 99, 130, 172, and 208.

TABLE 2.—*Average monthly discharge of South Fork of Republican River at Benkelman, Nebr.*

Month.	Number of observations.	Discharge.	
		Acre-feet (on surface).	"Section-feet" of ground water.
April	3	5,770	27.0
May	2	5,840	27.4
June	4	4,880	22.9
July	4	1,530	7.0
August	3	1,480	6.9
September	2	390	1.8
October	3	2,400	11.2
November	2	3,180	14.9
		25,470	119.1

A United States Geological Survey stream-gaging station is located on South Fork of Republican River near Benkelman, Nebr., where gagings were taken during a part of each year from 1903 to 1906. The estimated discharge of the river at this point is shown in Table 1. By averaging the monthly discharges in acre-feet for the four years the figures given in Table 2 were found. The third column of this table gives the average estimated discharge by months in acre-feet—that is, the number of acres the water would cover to a depth of 1 foot. The fourth column gives the same discharge in "section-feet"—that is, the number of sections of 640 acres each on which the ground water would be raised 1 foot if all of the water went to replenish the underflow, the gravels having a porosity of one-third. The data in this table are also presented graphically in figure 28. During the four months in which the river was not gaged—December, January, February, and March—as much if not more water flows away from the valley of the South Fork. Altogether the supply would suffice to raise the ground water 1 foot on 240 sections—that is, it would be 50 per cent more than would be necessary to replenish 80 sections if lowered 2 feet by pumping. This estimate is believed to be moderate, for, first, the time will probably never come when 80 sections of bottom land will be irrigated by pumping from the underflow; second, a portion of the water used for irrigation (probably more than 20 per cent) will find its way back to the ground-water supply; third, the local precipitation will increase the supply not only by the amount that falls directly upon the bottom lands but by the amount that drains into the valley from the hills on either side; and fourth, it is probable that the total discharge of 51,000 acre-feet per year for South Fork of Republican River is too small rather than too large.

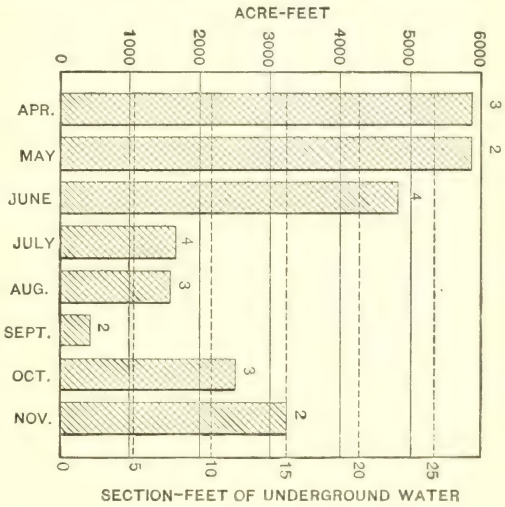


FIGURE 28.—Average monthly discharge (estimated) of South Fork of Republican River at Benkelman, Nebr.

The amount of water that escapes over the surface during the winter and spring floods is large in proportion to the size of the valley; the alluvial deposits afford about the only means of storing these flood waters, and their ability to perform this service is increased by pumping.

SPECIFIC CAPACITY.

At the time of the ground-water investigations only one pumping plant was recovering water for irrigation along South Fork of Republican River. This plant is in the SE. ¼ SW. ¼ sec. 9, T. 1 S., R. 38 W. It consists of an 8-horsepower gasoline engine, a centrifugal pump, and a 15-inch well. The well casing is made of 20-gage galvanized sheet iron, the lower 10 feet perforated to admit water. The perforations are vertical slits, perhaps 1 inch by one-fourth inch, 1 inch apart, placed in vertical rows about 1 inch apart. The casing extends down to shale, 24 feet below the surface of the ground, or 14 feet below the normal water level.

On September 16, 1908, after the plant had been in operation day and night for several days, the yield of the well was determined by pumping continuously for three hours into a reservoir. During these three hours of pumping the water rose in the reservoir 1.54 feet, to which must be added 0.24 feet for loss by seepage. The area of the water surface at the beginning of the test was 2,266 square feet and at the end 2,497 square feet. This gives a yield of 176 gallons a minute.

During the test the water in the well stood 12.5 feet below its normal level. Dividing the 176 gallons by 12.5 gives 14.1 gallons a minute for each foot of draw down of the water. This quantity is termed the specific capacity of the well. Dividing the specific capacity (14.1 gallons a minute) by 39.24, the total percolating area of the well casing in square feet, gives what is termed the specific capacity of the gravels; in this case 0.36 gallon a minute. The specific capacity is a factor expressing the readiness with which the gravel yields water to a well. In other words, it is the yield in gallons a minute of a well having 1 square foot of strainer surface when the water in the well is lowered 1 foot below its normal position. The specific capacity of this well would probably have been very greatly increased if the strainer end of the casing had been more closely perforated, so as to admit the water into the well more freely.

The specific capacity of the gravels in Arkansas River valley, near Garden City, Kans., runs from 0.11 to 1.3, the average of 12 tests being 0.41.[a] The specific capacity of the Richardson well compares favorably with these capacities, and a comparison of the water-bearing material in the two valleys indicates that the specific capacity of wells in the South Fork of Republican Valley may be greater than those in the Arkansas Valley.

[a] Slichter, C. S., The underflow in Arkansas Valley in western Kansas; Water-Supply Paper U. S. Geol. Survey No. 153, 1906, p. 56.

QUALITY.

Samples of ground-water taken from various wells in the valley were tested for chlorine with tenth-normal silver nitrate, for alkalinity with tenth-normal hydrochloric acid, for hardness with a standardized soap solution, and for total solids in solution by means of a Whitney electrolitic bridge. The results of these tests are given in Table 3 and are represented graphically in the lower part of Plate II. At St. Francis the total solids in solution run as high as 1,350 parts per million, whereas 600 is about the ordinary limit allowable for water to be used for irrigation. Nevertheless, with the exception, perhaps, of some of the water found along the northwest edge of the valley, these amounts are not large enough to be injurious to plant life, for the soil of the valley is of loose texture and lies upon a sandy subsoil, and the salts in solution are not the kind most injurious to plant life.

TABLE 3.—*Data concerning wells at stations at St. Francis, Kans., and 10 miles above St. Francis.*

Station.	Depth to shale.	Depth to water.	Velocity of underflow.	Chemical analyses of ground water.				Elevation of water plane above assumed datum plane.
				Total solids.	Chlorine.	Alkalinity.	Hardness.	
At St. Francis:	*Feet.*	*Feet.*	*Feet per 24 hours.*	*Parts per million.*	*Parts per million.*	*$CaCO_3$ (parts per million).*	*$CaCO_3$ (parts per million).*	*Feet.*
1	19.5	2.0	56.0	320	9	200	251	92.01
2	18.5	2.0	29.0	290	9	225	220	90.69
3	22.0	2.5	6.0	420	12	315	283	89.79
4	21.0	3.5	4.7	420	30	275	283	89.17
5	20.0	1.4	11.2	1,300	99	410	662	92.10
6	20.0	1.7	8.4	1,350	43	430	514	93.12
7	13.5	1.4	4.1					94.12
8	11.0	.5		1,050	37	396	407	
11								87.80
12	20.5	5.5						94.18
13	20.0	3.0						115.28
River				300	9	220	216	91.69
Finley				1,250	43	265	508	94.70
Ten miles above St. Francis: [a]								
23	7.5	2.5						95.0
24	13.0	5.4		360	10	265	280	94.2
26	17.5	6.8		380	12	262	255	95.3
27	18.0	5.0		340	10	260	299	96.1
28	22.5	9.6		290	9	205	292	100.4
29	22.0	8.2						99.3

[a] The elevations of water plane for stations 10 miles above St. Francis are referred to a second arbitrary datum plane.

PUMPING PLANTS.

GENERAL STATEMENT.

The investigations made in the valley of the South Fork of Republican River indicate that in almost any part of the bottom lands between St. Francis and Benkelman an ample supply of ground

water can be had for small pumping plants. The water-bearing gravels have an average thickness of 15 to 20 feet and contain enough coarse material to render it unnecessary to use fine-mesh strainers in the wells. In a large part of the bottom lands the depth to water ranges from 2 to 10 feet, so that the water may be pumped to the surface economically. The cost of pumping at any place will be controlled primarily by the cost of fuel and the distance the water must be lifted; and the answer to the question whether a pumping plant may be profitably installed must depend largely on the crops that can be grown and the prices at which they can be marketed.

CHARACTER OF WELLS.

The cheapest well for procuring ground water in the large quantities needed for irrigation is one that is from 12 to 15 inches in diameter and that extends through the water-bearing gravels to the Pierre shale, and, if practicable, for 2 or 3 feet into the shale. A strainer for such a well can be made by punching sheets of heavy galvanized iron with slots about one-eighth by 1 inch in size and then riveting the sheets into cylinders. The cylinders should be so rolled that the burr made by the punch will be inside the cylinder and the long diameter of the slots will be vertical in the well. A much better strainer can be made of metal purchased in sheets already perforated. Steel sheets 48 by 60 inches, perforated with hit-and-miss slots three-sixteenths by 1 inch and then galvanized, make ideal strainers. When rolled into cylinders these sheets form sections of a casing about 15 inches in diameter. In constructing the well these perforated sections should be put in place, one above another, to a point about 8 feet below the water level; from this point upward the casing should not be perforated.

AMOUNT OF WATER OBTAINABLE.

Wells constructed as just described will furnish at least one-third gallon of water a minute for each square foot of strainer surface in the well when the water in the well is lowered 1 foot by pumping. If the water in the well is lowered 10 feet by pumping, the quantity of water recovered should amount to about ten times as much, or 3.3 gallons per square foot of strainer. If a 15-inch well, the lower 10 feet of which is strainer surface, is placed in good water-bearing gravel, and if the pump lowers the water in the well 10 feet, the amount of water supplied by the well should amount to about 133 gallons a minute.

A 15-inch well in the Arkansas River valley (see fig. 27) has a capacity of 136 gallons a minute with 10 feet of drawdown. The gravel in which this well was sunk was not so good a water-bearer as some of that in the valley of Republican River.

A 9-inch well with an 8-foot strainer in the Cimarron River valley, Beaver County, Okla., sunk in ordinary clean gravel, such as is found near the center of the valley at St. Francis, had a capacity of 265 gallons a minute when the water plane was lowered 8 feet by pumping. Wells of this capacity could probably be sunk at two or more places where test holes were put down near St. Francis.

In the Republican River valley the yield of wells differs greatly. One well only a few hundred yards from another may furnish two or three times as much water. A small amount of the fine earthy material mixed with the sand and gravel will greatly cut down the yield. This fine material, usually loess washed down from the uplands, is found near the edge of the valley, especially where a draw or creek comes down from the uplands. As a general rule, the nearer a well stands to the center of the valley the greater is its capacity. In locating a pumping plant it is desirable first to put down a series of test holes in order to find good water-bearing material, especially if the plant is to be located near the edge of the valley or near the mouth of the creek.

METHOD OF SINKING WELLS.

Wells of diameters of 12 or 15 inches may be best sunk with an 8-inch or 10-inch sand bucket. As the sand is pumped out the casing is weighted at the upper end with sacks of sand and allowed to settle.

A pit should be dug to the water plane, or as deep as possible. Within this a larger temporary blank casing should be sunk 8 to 10 feet below the water plane. Within this temporary casing the permanent well casing and strainer should be placed and pumped down with the sand bucket. By this method the strainer part of the well will be sand-pumped down through the gravel from which water is to be drawn, and by the churning of the sand pump the gravel for several feet around the well will be washed free from a large part of the fine material which it contains. This is one reason why a strainer with large openings should be used. It will take more time and patience to sink a well in this way than to sink the unperforated temporary casing to shale and place the permanent casing inside, but if the velocity of the entering water is great there is a compensating gain in the removal of the fine material around the casing.

Care should be taken that the lower end of the permanent casing is well within the shale, so that there will be no possibility that

sand will be drawn into the well when the pump is started. After the final casing is in place the outer temporary casing should be slowly pulled out, and as it is withdrawn coarse gravel should be fed in, a little at a time, between the temporary and final casings. Care must be taken that the inner portion does not bind to the outer, so that both casings will be lifted. After the outer casing has been drawn it will probably be found that the well has filled up several feet with sand. This sand should be pumped out with the sand bucket. The end of the suction pipe should be placed as near the bottom of the well as possible, in order to remove any additional fine sand that might find its way into the well, which should be very little if the well is put down as described above. The object of digging the pit to ground water and inserting a temporary casing is to shut off the fine sand which is generally found above and for a short distance below the water plane, and to make it necessary to raise the sand bucket but little, if any, above the surface of the ground.

ARRANGEMENT OF WELLS.

At no place in the valley will it be possible to supply a 4-inch centrifugal pump from a single well. Three or four wells that yield 140 gallons a minute each should be connected with a single pump. The more wells used the less will the water plane be lowered and consequently the less the work that will be required of the engine and the less the fuel consumed. Not all of the reduction in the lift of the water is gain, however, because power will be lost in overcoming the friction due to the additional length of piping connecting the wells.

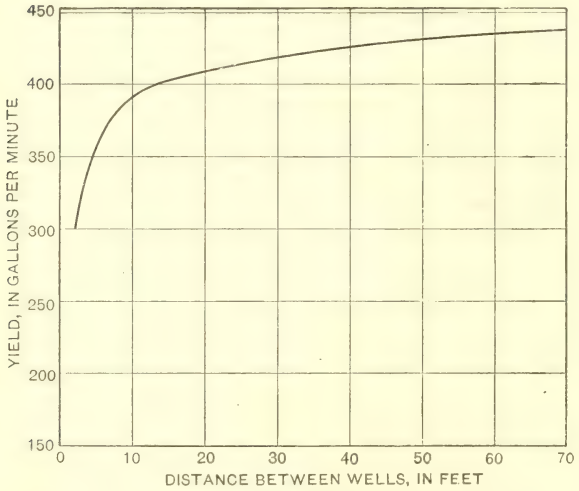


FIGURE 29.—Relations of three wells in the Arkansas Valley.

Since it is necessary to construct several wells in order to obtain the quantity of water required for an irrigation plant it becomes important to consider the best and most economical arrangement of the wells. In the Republican River valley perhaps the best method

is to sink a battery of three or four wells and connect them by suction pipes to the pump. These wells should be arranged in a line and placed 20 to 30 feet apart, with the pump near the middle of the line. Figure 29 represents in a rough way the interference of three wells with different spacing and shows why the wells should not be placed nearer together than 20 to 30 feet. If the water plane is lowered the same amount at all times, say 10 feet below the normal position, and the three wells are placed so far apart that there is no interference, their total yield will be 450 gallons a minute. If the wells are 40 feet apart, the yield will drop down to 425 gallons; if 30 feet apart to 420 gallons; if 20 feet apart to 415 gallons; and for a nearer spacing than 20 feet the yield would be considerably lessened. The construction of a plant having four wells is given in figure 30.

SELECTION AND INSTALLATION OF PUMPS.

It does not pay to purchase any but the best machinery for pumping, as poorly designed and poorly constructed plants eventually prove very expensive.

Probably the most satisfactory pump for use in irrigation is the centrifugal pump. It should be remembered, however, that there are on the market a great many kinds of small centrifugal pumps, which are designed for a great many purposes. The centrifugal pump used by the irrigator should be of the inclosed-runner type, provided with self-oiling bearings of the oil-ring type. Several pumps of this type can be had, and any of them will do good work if its size and design are adapted to the conditions under which it must work. The maker of the pump should have full information of all the conditions, including the distance that the pump must discharge the water above its outlet and the amount of suction or distance the water must be lifted below the pump inlet.

The efficiency of the centrifugal pump under actual working conditions is higher for large pumps than for small ones. Pumps having a discharge pipe less than 3 inches in diameter will show low efficiency. A centrifugal pump will work better and be more efficient if the suction pipe is made as short as possible, and on this account the pump should be placed as near the level of the water as may be consistent with the securing of a good foundation.

If the pump is to be driven by a belt it should be provided with a large pulley. The pulley usually supplied with a pump is so small that the belt slips on the pulley, so that the efficiency of the plant is greatly decreased. Of course, it is necessary to maintain a proper

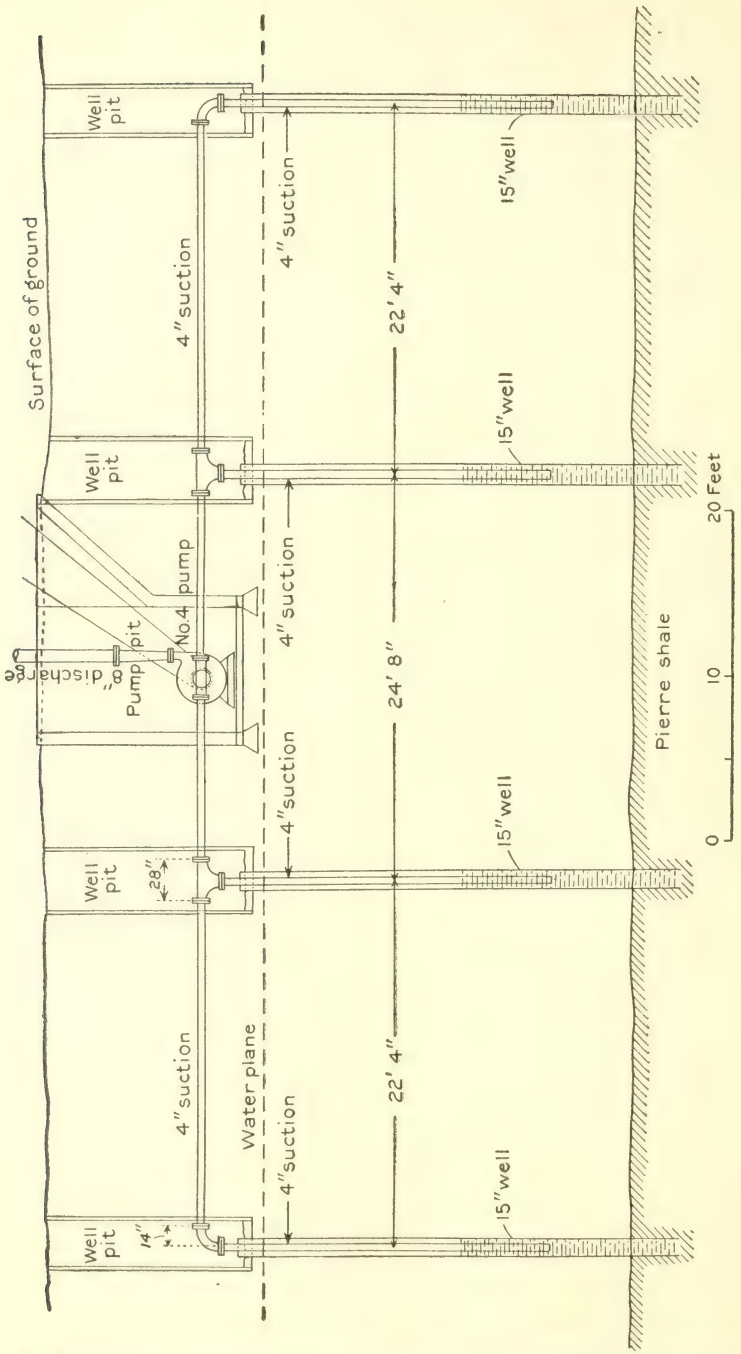


FIGURE 30.—Suggested arrangement of wells and pump designed to recover 400 gallons of water a minute.

proportion between the sizes of driving and driven pulleys, but both should be larger than those usually furnished with pumps and engines, say not less than a 12-inch pulley on a No. 4 pump.

The suction pipe on the pump and the discharge pipe should be large. A No. 4 centrifugal pump that draws water from a single well should have at least a 6-inch suction pipe, and the diameter of the discharge pipe should gradually increase from 4 inches at the discharge opening of the pump to 8 inches at a point 3 feet beyond the discharge opening and continue in this size to the flume or discharge conduit. Both the discharge and suction pipe should be galvanized spiral riveted No. 18 iron for 4-inch pipe and No. 16 iron for 6-inch pipe. The ends of the pipe should be provided with standard flanges for bolting together or for pipe fitting. Reducers of any size and length can be had or made to order. If three or more wells are connected to a No. 4 centrifugal pump the diameter of the part of the suction pipe that carries the water from a single well may be reduced to 4 inches.

A centrifugal pump loses its efficiency at once if it leaks air around the stuffing box or if there is an air leak at any place in the suction pipe. Many centrifugal pumps are now provided with a water seal around the stuffing gland that prevents leakage at that point.

A good centrifugal pump with inclosed impeller or runner should show an efficiency of about 60 per cent on a 30-foot lift. Single-stage centrifugal pumps, constructed with bronze impellers, made in two pieces so that the interior could be machined and smoothed, have shown an efficiency of about 80 per cent.

A large number of pumping plants are installed with foot valves at the bottom of the suction pipe. When these are provided a centrifugal pump is always ready to start after it is primed. The foot valves usually interfere very materially with the flow of water into the pipe, and it is undoubtedly more economical to omit them and place a flap valve at the upper end of the discharge pipe, which can be lowered when it is desired to start the pump. The foot valve is also undesirable in cold weather if the pump and suction pipe are above the frost line, as the pump and pipe may freeze if they are kept full of water. An ordinary cast-iron cistern pump connected to the top of the casing of the centrifugal pump can be used to prime the pump before starting.

The suction pipe usually installed by constructors of pumping plants is not only too small for the best results, but the elbows and tees used are very poorly adapted to the purpose intended. It is a common practice to use steam-pipe fittings for this purpose. In consequence the water is required to turn at sharp angles at the tees

and elbows and the best results can not be obtained. In order to avoid this difficulty "long-sweep" fittings should be purchased. These are standard trade goods and can be obtained from any of the large dealers in pipe fittings. If an elbow or tee is used next to the pump, it should be of the flanged type and bolted directly to the pump. Figure 31 shows the difference in the two kinds of fittings.

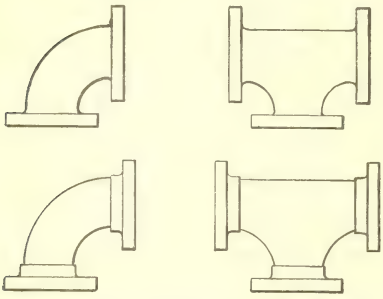


FIGURE 31.—Relative shape of standard and "long-sweep" pipe fittings.

ECONOMICAL LIFT.

It is very unlikely that it will pay to lift water under present conditions in the Republican Valley for a total distance of more than 30 feet, including the suction lift of the pump. If the pump lowers the water in the wells 10 feet, if the distance to water is 10 feet below the surface, if the discharge pipe is brought into a reservoir or flume 5 feet above the surface, and if 5 feet be added to cover loss of head due to friction in suction and discharge pipes, the total lift will be 30 feet. It will probably not pay to pump water to a greater height at any place in the valley, except for the irrigation of garden products and other high-priced crops.

ENGINES AND COST OF PUMPING.

If the total lift is 30 feet, if 450 gallons are pumped per minute, if the pump has an efficiency of 50 per cent, and if there is a loss of 10 per cent in the belt connecting the pump and engine, then it would require 7.6 horsepower to raise the water; that is, an 8-horse power engine would be large enough.

If possible the engine should be housed, or at least provided with a good canvas cover when not in use. Cotton waste should not be spared in keeping an engine clean, for a large amount of dust will be caught by accumulated grease, even when the engine is housed, and this will soon prove very injurious to the wearing parts.

A favorite engine for small pumping plants is the gasoline engine. Where the price of gasoline is high, it is very easy to make the cost of water prohibitive by the use of such power. Whether or not it pays to pump water by gasoline depends very largely not only on the distance the water must be lifted, but also on the kind of crop that is to be irrigated. Gasoline, even at a high price, is usually a cheaper fuel than coal in an ordinary steam engine of small horsepower. For plants requiring from 20 to 30 horsepower producer-gas generator

can be installed, which will keep the cost of pumping down to a minimum. A suction gas producer, using anthracite pea coal for fuel, should furnish power at the rate of 1 horsepower per hour for each pound and a half of coal consumed. At $8 per ton the cost of coal should be equivalent to gasoline at 4 to 6 cents a gallon.

In large plants, requiring from 50 to 100 horsepower or more, a condensing Corliss engine is sufficiently economical where the cost of coal does not exceed $3.50 to $4 per ton.

The cost of recovering ground water from wells is made up of four principal items—(1) cost of fuel and supplies, (2) cost of labor, (3) charge for depreciation and repairs, and (4) interest on the first cost of the plant or the capital invested. The first and third of these items are partly under the control of the owner of the plant. If the plant is carefully designed and well proportioned and if all its parts are good, the cost of fuel can be kept at a minimum and the charge for repairs and depreciation will be low. The depreciation will be at least as great when the plant is idle as when it is running, especially if the machinery is then neglected and carelessly exposed. The charge for repairs and depreciation will be not less than 10 per cent of the first cost of the plant.

A small pumping plant will recover not more than 50 per cent of the power delivered to the belt by the engine. The loss in the belt amounts to 5 to 10 per cent, the loss in the pump amounts to about 30 per cent, and the friction losses in the suction and discharge pipes range from 5 to 20 per cent. In order to secure economy in running it is important that the engine should be large enough to do the work, but not too large. The use of gasoline engines whose capacity is largely in excess of the requirements of the work involves great loss.

Tests of several pumping plants in the Rio Grande valley are reported by Slichter, who publishes[a] a table giving cost of fuel, interest, and cost of labor estimated for each acre-foot of water recovered. Slichter also gives similar facts concerning the cost of pumping water by small pumping plants in the Arkansas River valley in western Kansas,[b] and describes a test of a producer-gas pumping plant at Rockyford, Colo.[c]

At almost any point in the river valleys of the western plains complete pumping plants, including wells, machinery, and buildings can be constructed for about $100 per horsepower required, and exceptionally the cost may be as low as $60 per horsepower.

[a] Slichter, C. S., Observations on ground waters of Rio Grande valley: Water Supply Paper U. S. Geol Survey No. 141, 1905, p. 34.

[b] The underflow in Arkansas Valley in western Kansas: Water-Supply Paper U. S. Geol [illegible] No. 153, 1906, p. 55.

[c] Idem, p. 82.

STORAGE RESERVOIRS.

In order to irrigate economically from a pumping plant it is usually desirable to pump the water into a reservoir having a capacity equal to the amount of water the plant can furnish in six to eight hours. Such a reservoir is absolutely necessary for the best results with small pumping plants. If the supply of water exceeds 500 gallons a minute it is possible to dispense with the reservoir. Plants furnishing over 1,000 gallons a minute can generally be best operated without a reservoir.

A reservoir should be well puddled to prevent leaking. The reservoir at the Richardson plant loses by seepage 1 inch in water depth every hour. If the area of a reservoir is 2,500 square feet, this seepage amounts to 15,000 cubic feet a day, or enough to cover an acre 4 inches deep.

LOSS BY EVAPORATION.

Water should be pumped as near as possible to the place at which it is to be used. Although it is cheaper to construct and operate a

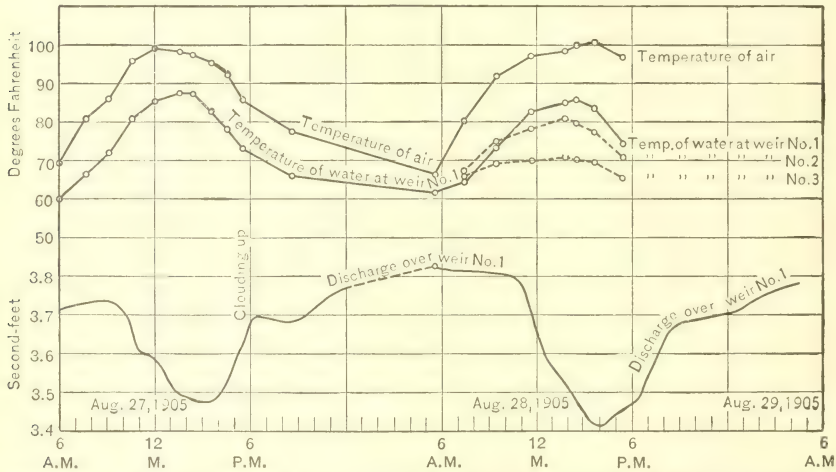


FIGURE 32.—Diagram showing loss by evaporation and vegetation on ditch 8,000 feet long near Ogalalla Nebr., August 27–28, 1905.

plant pumping 2,000 gallons than five smaller plants of the same combined capacity, the loss by evaporation and supplying plant growth along the ditch bank is considerable. In a ditch a mile long, carrying 4 cubic feet of water per second, this loss may be as great as 10 or 12 per cent during the warm hours of the day. Figure 32 shows the loss through evaporation and vegetation growing along the edges of a ditch 8,000 feet long. Each day there was a sudden drop in the discharge, beginning at about 9 a. m. and continuing until 4 p. m., after which the flow would increase very rapidly until 7 or 8 p. m. and remain comparatively constant during the night.

CONCLUSIONS.

The principal conclusions reached as a result of the investigation may be summarized as follows:

1. The source of the underflow is the precipitation in the drainage basin of the river.

2. The water-bearing gravel in the valley averages about 15 feet in thickness.

3. The water plane at St. Francis, Kans., slopes down the valley at the rate of 10.7 feet per mile.

4. The underflow of South Fork of Republican River moves at an average rate of 17 feet a day.

5. The rate of movement is, in general, much faster near the center of the valley than near its edges.

6. Better wells for irrigation can, in general, be sunk near the center of the valley than near its edges.

7. There is no danger that the underground water in the valley will be exhausted by pumping.

8. The water-bearing gravel contains enough large material to permit the use of a well strainer having openings as large as 1 inch long by three-sixteenths inch wide.

9. Except perhaps in a few localities along the northwestern side of the valley the quantity of dissolved salts in the ground water is not large enough to be injurious to plant life.

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UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

WATER-SUPPLY PAPER 259

THE UNDERGROUND WATERS OF SOUTHWESTERN OHIO

BY

M. L. FULLER AND F. G. CLAPP

WITH A DISCUSSION OF

THE CHEMICAL CHARACTER OF THE WATERS

BY

R. B. DOLE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1912

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THE UNDERGROUND WATERS OF SOUTHWESTERN OHIO.

By Myron L. Fuller and Frederick G. Clapp.

INTRODUCTION.

LOCATION AND AREA.

The district covered by this report is an area in southwestern Ohio extending from Ohio River on the south to the southern portions of

FIGURE 1.—Index map showing location and extent of area discussed in report.

Darke and Miami counties on the north, and from the Indiana State line on the west to central Adams and Highland counties on the east

(fig. 1). The area averages approximately 80 miles from north to south and 70 miles from east to west and contains about 5,600 square miles, or about one-seventh of the total area of the State.

The district includes the following counties: Adams (western half), Brown, Butler, Clark, Clermont, Clinton, Darke (southern part), Greene, Hamilton, Highland (western half), Miami (southern part), Montgomery, Preble, Warren. The principal cities are Cincinnati, Dayton, Hamilton, and Springfield.

OBJECT OF INVESTIGATION.

The region under discussion receives abundant rainfall, the precipitation averaging over 40 inches a year. The streams, however, are rather far apart and springs are few and of small volume. Moreover, as the region is densely populated, the inhabitants averaging about 150 to the square mile in the area as a whole and 50 in the rural districts, and as it contains many paper mills, distilleries, powder mills, and other manufacturing establishments, the surface waters are in many localities badly polluted by sewage and industrial wastes and are entirely unfit for drinking. For these reasons carefully protected ground-water supplies are highly desirable for domestic uses, especially in cities and crowded villages, where the nearness of the houses and the proximity of barns, privies, and cesspools may make wells unsafe sources of supply.

The value of pure water for public supplies can not be overestimated, the industrial loss resulting from a serious typhoid or other epidemic due to impure water often being of such magnitude as to seriously interfere with the prosperity of a town. People who a few years ago regarded any clear and cool water as satisfactory are now demanding that its absolute safety be established by proper examination and inspection, and although in some localities a doubtful water may occasionally be accepted, condemnation of the supply and of those responsible for its installation is certain to follow its continued use.

Not only is the problem of procuring pure water for drinking and for other domestic uses recognized as urgent in the cities and villages, where it is not unusual to find practically every well more or less polluted, but it is of great importance in the country. Many farm wells are located in or near barnyards or hogpens and are contaminated by refuse blown into them by the winds, as well as by the bodies of snakes, mice, rabbits, and other animals that may fall into them in their search for water in dry seasons. Many wells that furnish drinking water are situated on low ground and receive the drainage from houses and yards, being thus sources of grave danger. To the farmer, therefore, information both as to the proper construction of wells and as to the best sources of water will be of great value.

One of the most important uses of water in many regions is for locomotive boilers. For the economical running of trains, especially freight trains, water must be provided every few miles. Where permanent streams are available and are not too muddy they generally furnish satisfactory supplies; but over many areas the streams are few, are far apart, and many of them go dry in times of drought. In such places wells must be the sources of supply.

In southwestern Ohio immense quantities of water are required in industrial processes. In the manufacture of paper, especially, a single mill may use several hundred thousand gallons of water daily, and as the water of the streams is generally too muddy and the quantity too uncertain for this purpose, wells are largely used. Many other industries, especially those located in cities where the rates charged for the public service practically prohibit its use, have urgent need of ground-water supplies.

The people of the vicinity generally know when a well has succeeded in obtaining a satisfactory supply, but knowledge of the conditions that determine the success of the well or of the limits to which the favorable conditions extend is as a rule scanty, and many thousands of dollars have been wasted in southwestern Ohio and elsewhere in well drilling in places where a geologist would have pronounced the attempt hopeless. Information regarding the proper construction of wells is also urgently needed in order that the largest possible supplies and the best and purest water which a well is capable of affording may be obtained.[1]

SOURCES OF INFORMATION.

EARLY STUDIES.

Previous to the investigations for the present report no specific study of underground waters had been conducted in the region, although some attention had been paid to the water resources by the parties investigating the geology of a number of counties for the State Survey, under Edward Orton, and by Frank Leverett in his studies of the drift of the region. The results of the former have appeared in the county reports of the State Survey and in a paper on the rock waters published by the United States Geological Survey.[2] The results of Leverett's work have appeared in several reports of the National Survey.[3]

[1] See Bowman, Isaiah, Well-drilling methods: Water-Supply Paper U. S. Geol. Survey No. 257, 1911.

[2] Orton, Edward, The rock waters of Ohio: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 4, 1898, pp. 633–717.

[3] Leverett, Frank, The water resources of Indiana and Ohio: Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 4, 1897, pp. 419–559. Also, Underground waters of eastern United States: Water-Supply Paper U. S. Geol. Survey No. 114, 1905, pp. 265–270.

BIBLIOGRAPHY.

The more important publications which relate in part to the underground waters of Ohio are listed in the following bibliography. Many of these reports are, however, out of print and inaccessible.

FULLER, MYRON L., LINES, E. F., and VEATCH, A. C., Record of deep-well drilling for 1904: Bull. U. S. Geol. Survey No. 264, 1905, 106 pp.

Lists a number of new wells in Montgomery County.

FULLER, MYRON L., and SANFORD, SAMUEL, Record of deep-well drilling for 1905: Bull. U. S. Geol. Survey No. 298, 1906, 299 pp.

Lists new wells in Brown, Darke, and Greene Counties.

FLYNN, BENJAMIN H., and FLYNN, MARGARET S., The natural features and economic development of the Sandusky, Maumee, Muskingum, and Miami drainage areas in Ohio: Water-Supply Paper U. S. Geol. Survey No. 91, 1904, 130 pp.

Includes a discussion of many of the public water supplies of southwestern Ohio, including those from springs, wells, and collecting galleries.

HUSSEY, JOHN, Report of the geology of Miami County: Rept. Geol. Survey Ohio, vol. 3, pt. 1, 1878, pp. 468–481.

Notes the abundance of springs at the horizon of the "Clinton" limestone, some of which are large enough for power development. Describes the large spring at West Milton and discusses the conditions of the underground collection of water. The wells of the drift and the evidence which they afford of buried channels are also considered (pp. 469–470).

LEVERETT, FRANK, The water resources of Indiana and Ohio: Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 4, 1897, pp. 419–559.

After considering the physical features, drainage, lakes, etc., of the region (pp. 426–474), discusses underground waters, including wells of the drift, shallow and deep rock wells, subterranean drainage lines, springs, analyses of the waters, etc. (pp. 474–501), and gives extended descriptions of the water supplies of cities and villages (pp. 502–559).

——— Glacial formations and drainage features of the Erie and Ohio basins: Mon. U. S. Geol. Survey, vol. 41, 1902, 802 pp.

No special discussion of the waters of the drift, but refers incidentally to wells and records, especially to the flowing wells of Ohio (see index of monograph).

LINDENMUTH, A. C., Report of the geology of Darke County: Rept. Geol. Survey Ohio, vol. 3, pt. 1, 1878, pp. 496–518.

Describes the lime, magnesia, and sulphur springs of various beds (pp. 496, 509, 517), and notes the abundance of good water in both drift and rocks (p. 517).

ORTON, EDWARD, Report on geology of Montgomery County: Geol. Survey Ohio, Rept. of Progress in 1869, pt. 3, pp. 143–171.

Describes the association of springs with the "Clinton" limestone (pp. 162–163).

——— The geology of Highland County: Geol. Survey Ohio, Rept. of Progress in 1870, pp. 255–294.

Notes prevalence of springs at shale layers in "Niagara" limestone (p. 275).

ORTON, EDWARD, The cliff limestone of Highland and Adams counties: Geol. Survey Ohio, Rept. of Progress in 1870, pp. 295–308.

Describes springs at top of the shale layers in the "Niagara" limestone (pp. 302, 304).

——— Geology of Hamilton County: Rept. Geol. Survey Ohio, vol. 1, pt. 1, 1873, pp. 419–434.

Gives sections and notes on wells near Cincinnati.

——— Geology of Clermont County: Rept. Geol. Survey Ohio, vol. 1, pt. 1, 1873, pp. 435–449.

Notes scarcity of springs and considers use of cisterns and wells in both rock and drift deposits (pp. 439–440, 446).

——— Geology of Clark County: Rept. Geol. Survey Ohio, vol. 1, pt. 1, 1873, pp. 450–480.

Describes springs of the "Niagara" limestone (pp. 465–466, 469).

——— Report on the geology of Greene County: Rept. Geol. Survey Ohio, vol. 2, pt. 1, 1874, pp. 659–696.

Discusses in detail the water-supply conditions of the county (pp. 690–696), including the "Clinton" and "Niagara" spring horizons, and horizons affording water to wells, the conditions leading to the contamination of ground waters, etc., and gives a full description of Yellow Springs and their surroundings.

——— Report on the geology of Warren County: Rept. Geol. Survey Ohio, vol. 3, pt. 1, 1878, pp. 381–391.

Discusses the wells and springs of the drift and the "Clinton" and "Niagara" limestones, and points out the need of cisterns in the blue limestone (Richmond and Maysville) districts. A large spring used for power development near Springboro is mentioned (pp. 388–389).

——— Report on the geology of Butler County: Rept. Geol. Survey Ohio, vol. 3, pt. 1, 1878, pp. 392–403.

Notes deficiency of ground water in the blue limestone (Richmond and Maysville) and in regions of thin drift. Cisterns are recommended (p. 403).

——— Report on the geology of Preble County: Rept. Geol. Survey Ohio, vol. 3, pt. 1, 1878, pp. 404–419.

Notes prevalence of springs, sometimes marked by petroleum shows, at horizon of "Clinton" limestone (pp. 406–408).

——— The Trenton limestone as a source of oil and gas in Ohio: Rept. Geol. Survey Ohio, vol. 6, 1888, pp. 101–310.

Contains notes on wells drilled for oil and gas in the several counties of southwestern Ohio, numerous detailed records, and notes on waters encountered or on casing used.

——— The rock waters of Ohio: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 4, 1898, pp. 633–717.

Discusses the geology (pp. 638–650) and considers the waters of various formations from Carboniferous to Ordovician, inclusive (pp. 651–696). Flowing rock wells and artesian wells of buried glacial channels are described (pp. 697–717).

PEALE, A. C., Lists and analyses of the mineral springs of the United States: Bull. U. S. Geol. Survey No. 32, 1886, 235 pp.

Gives list of mineral springs of Ohio, including those of the southwestern counties; contains analyses of artesian well water from Cincinnati; of salt well at Ludlow Grove, Hamilton County, Yellow and Bellbrook Magnetic Springs in Greene County, and Cedar Spring, Preble County.

FIELD AND OFFICE WORK.

The field work on which this report is based was begun August 1, 1906, by M. L. Fuller, assisted by S. R. Capps, with J. R. Evans serving as chemist until about September 1, from which date to the close of the work late in September the chemical work was performed by H. N. Parker. From September 1 to 20 F. G. Clapp, acting under M. L. Fuller, had charge of the party. The complete analyses in connection with the work were made by R. B. Dole, assisted by M. G. Roberts, and the discussion of the chemical character of the waters has also been prepared by R. B. Dole.

The work included the geologic tracing and correlation of the rock formations, a study of the water-bearing capacity of each formation outcropping at the surface or encountered by wells, the determination of the depth and yield of the waters, the study of the mineral springs, and the investigation of the public water supplies. Records of deep wells were procured, drillers were interviewed as to methods employed and general water conditions, and statistics were gathered in regard to the shallow wells in rock or unconsolidated material. The chemical work included field examinations of waters from each of the several classes of drift and rock formations and determinations of the carbonates, sulphates, chlorides, and iron. Complete analyses of samples of about 35 waters were made at the Washington laboratory, and analyses were obtained from owners of many wells. In the study of public supplies special attention was given to the sanitary quality of the water, with a view to determining sources of pollution and to making recommendations as to their removal.

The text relating to Preble, Butler, and Hamilton counties was prepared by F. G. Clapp, and the general discussion and the text relating to the other 10 counties was prepared by M. L. Fuller. Frank Leverett supplied the details of the distribution of the drift for Plate II, and M. L. Fuller and E. O. Ulrich most of the geology for Plate I. E. O. Ulrich and J. M. Nickles also assisted very materially in the preparation of the geologic discussions. Many drillers and well owners have also heartily cooperated in the work, and to them grateful acknowledgment is hereby made.

TOPOGRAPHY.

RELIEF.

Southwestern Ohio is in the main a plateau that stands between 800 and 1,100 feet above sea level; but the continuity of its surface is broken (1) by the deep valleys of the Ohio, Miami, Little Miami, and minor rivers and their tributaries, with bottoms extending from 100 feet or more below the crests of the adjoining uplands in the

northern part of the area to over 400 feet below it in the vicinity of the Ohio; and (2) by the irregular morainal and less numerous rock hills rising above it. Of the subordinate features of the valleys the bluffs, terraces, and alluvial plains are the most interesting.

UPLANDS.

Nearly the entire surface area of the district under discussion belongs to the broad plateau that extends throughout Ohio and covers the greater portions of most of the adjoining States. Although marked by numerous deep valleys, some of them so close to one another that they are separated only by narrow ridges, the intervening crests generally stand very near the level of the plateau of which they are the remnants. The plateau, however, is not absolutely flat, but rises gradually from a general level of about 900 feet near the Ohio to about 1,100 feet in the northeastern and eastern portions of the area.

Near the Ohio, and for 10 or in some place 15 miles or more north of its valley, the plateau is broken by numerous deep valleys and ravines, the more important of which are those of Miami and Little Miami rivers and Mill and Whiteoak creeks. Farther back the crests begin to widen and the flat remnants of the general surface are easily recognized. These gradually become broader to the north until flat surfaces many miles in extent are found.

VALLEYS.

Under the head of valleys are included all the depressions below the plateau except a few sags, so shallow as to be hardly noticeable, which here and there indent the surface. All of the valleys have been cut by streams that flow across the plateau, although several, such as that along the western border of Hamilton County, that leading from Hamilton to St. Bernard and thence to the Little Miami near Madisonville, that extending from near Middletown to South Lebanon, that cutting across a bend of the Little Miami near Lebanon, that connecting Mad River with the Little Miami Valley south of Osborn, and that extending from the Miami near Tippecanoe to the Mad River Valley near Osborn, are no longer occupied by streams, having been produced by waters flowing from the ice sheet which once occupied the region (Pl. II) or by the present streams when flowing in channels since abandoned.

The larger valleys are those of the Ohio, Miami, and Little Miami or of former channels of these streams. Of these, the Miami Valley has the broadest bottom, its width being 1 to 3 miles or more: the Ohio Valley is in few places more than a mile in width in this region.

In general the valleys become shallower to the north, where they have a depth of only 100 or 200 feet below the adjoining upland, as compared to 400 feet or more near the Ohio. Near the Ohio the ravines formed by the small tributaries are a striking feature, cutting the surface into a complex series of sharp-crested ridges and V-shaped ravines, many of which, although very narrow, are hundreds of feet deep.

Of the minor features of the valleys the terraces are of most interest. They occur mainly along the Ohio and lower courses of Miami and Little Miami rivers and Mill Creek and consist of flat-topped remnants of deposits that once filled a portion of the valleys to about 600 feet above sea level.

MORAINES.

The moraines are highly irregular topographic features, ranging from low rounded knolls to high hills and ridges characterized by sharp knolls and basins. In general they have no great height in southwestern Ohio, although a few rise 100 feet above the surrounding surface. Neither do they form high or continuous ridges in this region.

DRAINAGE.

The drainage of southwestern Ohio is here described because the considerable development of the underground waters is a direct result of the inferiority of the surface waters for many uses.

Ohio River, the main stream of the region, rises in the mountains of Pennsylvania and West Virginia in regions where the rocks are prevailingly sandstone and shale with but little limestone and where there is either no drift at all or only drift composed of non-lime-bearing material. As a result the Ohio water is low in lime and magnesia and gives but little trouble in boilers. Unfortunately, however, it is very muddy and is undesirable for many industrial uses. It is also badly polluted by sewage from Pittsburgh and many small cities and towns, which makes it very dangerous for domestic use.

Of the tributaries of the Ohio, Miami and Little Miami rivers and Mill and Whiteoak creeks are the most important. Unlike the Ohio, all of them have their sources either in limestone regions or in areas covered by highly calcareous drift from which the waters dissolve large quantities of lime and magnesia. These waters are, therefore, unfit for boiler use without treatment, and because of their muddiness are likewise unsuitable for many industrial uses. Their muddiness and the shortness of supply in times of drought has led to the sinking of numerous wells to supply the paper and other mills along the Miami.

CLIMATE.

Southwestern Ohio has a warm, moist climate in summer and a moderately cold but humid climate in winter. The rainfall is very equally distributed through the four seasons, from which it follows that somewhat over three-fourths of the precipitation occurs when the surface is unfrozen and when the water can penetrate the ground and join the underground supply. The evaporation is moderate, little ground water being lost in this way. In fact, the climatic conditions are favorable for the storage of large supplies in the ground, and the absence of these, except in the valleys, is due to the imperviousness and small porosity of the soils and rocks.

Some of the statistics of climate and rainfall having a bearing on underground waters are given in the following table:[1]

Climate and rainfall statistics at stations in southwestern Ohio.

	Cincinnati.	Dayton.	Portsmouth.
Precipitation (inches):			
Spring	9.9	9.8	10.4
Summer	10.9	9.9	11.5
Autumn	7.9	8.0	8.5
Winter	9.7	8.9	10.0
Annual	38.4	36.6	40.4
Temperature (°F.):			
Maximum	105	108	106
Mean maximum	64	65	67
Minimum	−17	−28	−18
Mean minimum	47	42	45
Mean annual	55	53	56
Average days over 90°	25	36	37
Average days under 32°	80	102	89
Frost:			
Latest killing frost in spring	Apr. 24	May 5	May 30
Earliest killing frost in autumn	Sept. 30	Sept. 19	Sept. 3

GEOLOGY.

STRATIGRAPHY.

GENERAL SUCCESSION OF STRATA.

The rocks of southwestern Ohio, restricting the term "rocks" to the hard consolidated beds commonly so called, are predominately limestone, every formation exposed at the surface being chiefly of this character, except the Eden and Utica shales, and even in the Eden many thin layers of limestone are interspersed with the shale at intervals of a few feet. Beneath the surface the known rocks with one exception—the St. Peter sandstone—are of similar charac-

[1] Compiled from the climatologic report of A. J. Henry: Bull. U. S. Weather Bureau No. Q, 1906, p. 714.

ter. This succession of hundreds of feet of limestone with almost no sandy water-bearing beds, makes the problem of water supply especially difficult. Fortunately, however, the surface is covered by a sheet of unconsolidated pebbly clay underlain locally by some sand and gravel, and nearly all the larger valleys are deeply filled with sand, gravel, or unconsolidated glacial material. The age, thickness, character, and water supply of the rocks are shown in the table given below. The distribution of the hard rocks is shown by the geologic map (Pl. I) and that of the unconsolidated material by the map of the Quaternary deposits (Pl. II).

Geologic formations in southwestern Ohio and their water supplies.

System.	Formation.	Character and thickness.	Water supply.	
			Weathered outcrops.	Deeper drilled wells.
Quaternary.	Alluvium. Terrace gravels. Loess. Wisconsin drift. Illinoian drift. Old gravels.			
Carboniferous.	Mississippian sandstone.			
Devonian.	Ohio shale.			
Silurian.	"Helderberg" limestone.			
	"Niagara" limestone.[a]	Bedded or massive gray to buff limestone, varying from granular to compact and commonly characterized by small openings lined with minute crystals. Thickness, 250 feet.	Considerable water yielded to shallow wells.	Moderate amounts usually found in basal layers just above contact with underlying "Clinton" limestone or above particular included layers of shale. Less amounts in joints or solution passages in other portions.
	"Clinton" limestone.[a]	Massive buff to pinkish horizontal or cross-bedded limestone, composed largely of minute shell fragments. Few joints or bedding partings Thickness, 50 feet.	Amounts generally small, but some shallow wells obtain supplies. Usually acts as impervious bed and gives rise to springs along upper contact.	Moderate amounts in joints, bedding planes, and solution passages; springs numerous at top and bottom.

[a] Niagara as used by the Survey includes all of the limestone described in this report as "Niagara" and "Clinton," but in order to avoid confusion to the reader accustomed to the old nomenclature, and because of the lack of established names for the subdivisions here recognized, the use of the old names is continued in this report.

GEOLOGIC MAP OF SOUTHWESTERN OHIO

Geologic formations in southwestern Ohio and their water supplies—Continued.

System.	Formation.	Character and thickness.	Water supply.	
			Weathered outcrops.	Deeper drilled wells.
Ordovician.	Richmond and Maysville formations.	Gray to blue limestone layers 2 to 10 inches thick, alternating with shales. Prevailingly calcareous throughout most of thickness, which is 550 feet.	Yields moderate supplies to shallow wells.	Amount of water very variable, the majority of deep wells obtaining very small supplies or none at all. Water in some wells brackish and in a few slightly sulphurous.
	Eden and Utica shales.	Gray shales, weathering brownish. Thickness, 250 feet.	Furnishes small supplies to shallow wells.	Rarely water bearing. No successful deep wells known.
	Point Pleasant formation (contains true Trenton fossils).	Dark, hard, compact shale; layers 2 to 10 inches or more thick, alternating with beds of impure gray limestones of similar thickness. Formation, 150 feet thick.	Outcrop is below level of Ohio flood plain. Not utilized by shallow wells.	Carries water locally, but success of drilling is uncertain. Some of the water is salty or sulphurous.
	"Birdseye" limestone (so-called "Trenton" limestone of drillers).	Massive compact grayish limestone, breaking with conchoidal fracture. Thickness, 600 feet.	Does not outcrop in southwestern Ohio.	More or less water generally present but commonly salty. Not to be depended on for supplies of fresh water.
	St. Peter sandstone.	Porous calcareous sandstone. Thickness, 400 feet.	Does not outcrop in southwestern Ohio.	Yields abundant supplies of "Blue Lick" sulpho-saline water, which rises 175 feet above low water of Ohio.
Cambrian and Ordovician.		Varicolored dolomitic limestones and marbles with possibly shale in some places. Thickness, 3,000 feet, more or less.	Does not outcrop in southwestern Ohio.	Carries little or no water at depths at which it occurs in southwestern Ohio.
Cambrian.		Probably prevailingly sandy (not penetrated).	Does not outcrop in southwestern Ohio.	Never penetrated in southwestern Ohio. Waters likely to be strongly mineralized and unusable.

UNCONSOLIDATED DEPOSITS.

ALLUVIUM AND GLACIAL VALLEY FILLING.

Alluvium comprises stream deposits such as the gravel, sand, or clay fillings of the valleys. In southwestern Ohio it is present in greater or less amounts in all valleys, except a few sharp ravines near

the Ohio and other large streams, where the small tributaries may flow on the bare rock. Naturally, the alluvium is considerably developed along Ohio River, where it has a depth of 100 to 168 feet, as shown by the bridge, waterworks, and well borings at or near Cincinnati. Its width in places may be 2 miles or more. Similar deposits occur along the Miami, Little Miami, Mill Creek, and numerous other rivers and large creeks, some of them reaching a width of 1 to 1½ miles, as on the Little Miami near Cincinnati. Few borings have been sunk through the alluvium in these valleys, but the depths in their lower portions are probably very similar to those in the Ohio. The thickness of the deposits doubtless decreases gradually upstream to the north, although wells as much as 70 feet deep failed to reach rock in the valley of Miami River at Dayton.

Superficially the alluvium generally consists of a sandy silt, but sand or gravel is usually found not far from the surface and continues to the bottom, except for a few more clayey beds at intervals. According to the statements of drillers, sand predominates in most wells, the gravels usually being rather fine and in beds of no great thickness. Probably, however, the tendency is to underestimate the amount of gravel, as usually only the sand is brought to the surface from the well. In fact, most of the wells, being of the driven type, give little evidence of the materials penetrated.

The pebbles in the gravel include many granitic fragments, presumably from the Canadian highlands, and have evidently been derived from the glacial drift of the region. Not all of the alluvium is of recent origin, however. In fact, except within 15 or 20 miles of the Ohio the greater portion is older than the last ice advance and is overlain in places by distinct morainal deposits of that stage. In general, however, the drift does not appear at the surface, apparently being covered by a relatively thin coating of glacial outwash or recent alluvium. It is probable that many of the reported clay layers are really beds of till. The drift layers are not clearly recognized in wells and are doubtless generally of no great thickness.

The surface elevation of the alluvium ranges from 450 or 500 feet near the Ohio to about 900 feet in the northern part of the area.

TERRACE GRAVELS.

Terrace gravels differ from alluvium in being the result of past rather than present stream action, for they stand distinctly above the level of existing flood plains. In general, the terrace materials are somewhat coarser than the alluvium, gravels as a rule largely predominating. Sand and clayey sand layers are not uncommon, however, and serve to collect the waters, which not infrequently deposit enough iron along the upper contacts to bind the sand or gravel into a hard stony mass, known locally as "cement rock." One of

MAP OF SOUTHWESTERN OHIO, SHOWING QUATERNARY DEPOSITS

these layers (Pl. VI, *B*, p. 44) is very near the surface, but others occur at greater depths and have an important influence on ground-water supplies. Many of the pebbles are granitic, having been derived from drift materials brought down by the ice from the Canadian highlands.

The terraces are found mainly along the valley of the Ohio and not more than 15 or 20 miles up the valleys of its tributaries. In the immediate vicinity of the Ohio they reach a maximum elevation of 600 feet and are covered with several feet of the fine yellowish clayey silt known to geologists as loess. The best example of this high terrace is in the broad gravel-filled depression, supposed to be an old channel of the Ohio, connecting the present valleys of Little Miami River and Mill Creek northeast of Cincinnati. Madisonville, Oakley, and Norwood are upon its crest, and St. Bernard and Bond Hill rest upon an extension which runs up Mill Creek valley east of Carthage, Hartwell, and Wyoming to Reading. Along the Ohio few terrace remnants are left, but in protected spots a few benches may be seen. North of Cincinnati the materials are mainly gravels, but some old till beds of considerable thickness may be included. In many places the gravel layers have been cemented by iron and break away in big conglomerate bowlders where the deposits are cut by streams.

From the level of the higher terrace down to a few feet above the present flood plains of the streams are a number of intermediate gravel terraces. Of these the 550-foot terrace near the Cincinnati pumping station at California, the 550-foot terraces on both sides of the Ohio near Home City, the 570 and 600 foot terraces at Terrace Park and Milford on the Little Miami, the 550 to 600 foot terraces at many points along the Miami south of Hamilton, as well as the less extensive benches along many of the smaller tributaries, should be mentioned.

Along the tributaries of the Ohio the alluvium gradually rises upstream, approaching ever nearer to the altitude of the benches, which are more nearly flat, until at 15 to 20 miles from the Ohio it reaches the level of the highest loess-covered terrace and merges with it. Farther up the alluvium everywhere covers the terrace, reaching in the northern part of the area altitudes of over 900 feet, or 300 feet higher than its level near Cincinnati.

LOESS.

The loess, locally known as yellow loam, yellow clay, etc., is a fine, nearly structureless silt, with practically no coarse grains of any kind. It is yellowish buff in color, and although somewhat plastic when wet, is not a true clay. It contains few if any pebbles,

and in this region is rarely if ever distinctly banded. It occurs at all elevations from that of the 600-foot terrace described in the preceding section up to the highest crests near the Ohio at something over 900 feet. It is not found in place below the 600-foot level, nor does it occur north of the southern limits of the last or Wisconsin ice advance. (See Pl. II.) In southwestern Ohio the upland loess seems to be mainly if not altogether the result of wind deposition, but it is possible that the loess of the valley terraces is water deposited and may have been, in fact, the original source of the upland material.

MORAINAL DRIFT.

Morainal drift is the term applied to the ridges of gravel or pebbly clay formed at the margins of the ice sheets that invaded the region in the geologic epoch immediately preceding the present. They are not true connected ridges, but are rather hills irregularly grouped together into more or less well-defined belts. (See Pl. II.) The older drift sheet thins out gradually to a mere fringe of pebbles, with no noticeable ridge at its edge; but the later or Wisconsin drift is marked by a number of ridges both at its southern limit and at several points where it halted temporarily during its retreat. Being formed mainly at the ice margins where considerable water resulted from melting, morainal deposits are generally gravelly and lack the compactness characteristic of drift which has been overridden by the heavy ice sheet; in some places, however, they contain considerable amounts of subglacial till. The gravel is commonly stratified, but generally the layers are very irregular and slope at high angles, owing to their deposition by tumultuous waters. In general they rest on till surfaces, which form impervious bottom layers. The ridges are not commonly very high, 20 to 30 feet being a common maximum on the upland, though exceeded in some places; in the valleys, especially on the sides, the ridges are much more conspicuous.

TILL.

The till is a heterogeneous mixture of clay and pebbles, with sporadic bowlders. In southwestern Ohio there are at least two tills representing differing glacial stages, the older being known as Illinoian and the younger as Wisconsin. The Illinoian, in its upper weathered portion, is yellowish or reddish, but below a depth of 10 or 15 feet it is an unoxidized grayish mass. In it clay predominates, making a firm, compact, impervious mass, in which pebbles are relatively few and of small size. The Wisconsin commonly contains less clay and more numerous and larger bowlders, consisting largely of limestone, shale, or other local rocks, though including many of granite from Canada. The mass is generally structureless, but in places an indistinct banding

MAP OF SOUTHWESTERN OHIO, SHOWING THICKNESS OF WATER-BEARING SURFACE DEPOSITS

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may be noted, and more rarely a thin band of stratified gravel is seen. The distribution of the till is shown by Plate II. It will be noted that with the exception of the valleys and the southern portions of Brown and Adams counties the whole of the region is covered with the till mantle. The map also brings out the limits of the late drift sheet and the extension beyond it of the earlier glacial drift. Near Ohio River and along the eastern margin of the outer drift the deposits are very thin, but the thickness increases to the northwest until in the northern part of the area the true drifts have a local united thickness of 100 to 150 feet or more. The variations in the thicknesses are shown on Plate III.

The till mantles the entire uplands and in places extends beneath the valleys (Pl. II), although it is not usually seen because of the covering of later alluvium. In the Ohio Valley most of the till has been removed by erosion since its deposition and it is now only found on the uplands.

The till represents accumulations of glacial materials dragged along and deposited beneath the ice sheets which covered the region in the geologic epoch immediately preceding the present. The layers of gravel and sand represent the work of streams or other bodies of water occurring beneath the ice. The lower and older drift is made up mainly of materials derived from the weathered rock surface over which the ice moved, the major part being from local rocks and a smaller proportion from Canadian rocks. The later or upper drift has less material derived directly from the local rocks, the larger proportion coming from the earlier drift or loess over which the ice moved, but with a considerable admixture of rock fragments from Canada.

OLD GRAVELS.

On the uplands southeast of Mount Washington, a few miles east of the mouth of Little Miami River, a small area of sand and gravel, apparently underlying loess and old till, appears to be of very early origin, its accumulation probably having taken place either in the latter part of the Tertiary period or in the early part of the Pleistocene or "glacial" epoch. This is borne out by the finding of mastodon teeth in a well sunk at Mount Washington. The gravel in which the fossils were found lies only 15 feet below the surface and consists of large flat pebbles standing partly on end, as in many of the present streams of the region, indicating that the stream was a rapid one. The entire deposit is very thin, shale being entered at 20 feet. The gravels have an altitude of 700 to 750 feet and are limited to a square mile or two southeast of Mount Washington, known locally as the American Flats, and to a much smaller area at the northern edge of the town.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.[1]

Character.—The "Niagara" limestone of southwestern Ohio is about 250 feet thick. In color it varies from very light gray through darker and bluish gray to buff. In general it is rather massive, presenting relatively few bedding planes. In fact, in the large quarry north of Mad River west of Springfield the writer did not see a single parting in a quarry face 50 feet in height, and even on blasting the rock broke into irregular fragments without reference to any structural planes. Elsewhere, however, the bedding is very marked, though in some places it is inconspicuous until brought out by weathering (Pl. VII, *A*, p. 45). The difference in the spacing of the parting planes in the lower unweathered and in the upper weathered portions is very noticeable. The texture varies from compact to granular, the former prevailing in the grayish types, and the latter being more common in the more open and therefore more weathered buff varieties. Many small openings varying in width from a fraction of an inch upward occur and are generally lined with coatings of minute crystals. In a very few places these openings are so numerous as to give the rock a superficial resemblance to the calcareous tufa deposited by limestone springs. Fossils are present, but are not nearly so numerous as in many other formations. They indicate a marine origin for the limestone.

The "Niagara" limestone outcrops around the borders of the region but dips gently away at the rate of 5 to 10 feet a mile both to the north and east. (See Pl. I.) It is the highest rock in the area, being overlain only by the glacial drift. The elevation of its outcrop commonly ranges from 900 to 1,000 feet.

"CLINTON" LIMESTONE.[1]

The "Clinton" limestone of southwestern Ohio, a relatively thin bed nowhere more than 50 feet thick, occurs at the base of the "Niagara" limestone and is shown on the geologic map (Pl. I) as a narrow band just south and west of the outcrop of the "Niagara." It is predominantly of a buff color but is nearly always characterized by a pinkish tinge or by streaks of red which suggest the iron-bearing layers of other regions and assist greatly in its identification. It seems to be composed largely of minute fragments of marine fossils which were rolled about by the sea and finally deposited in horizontal

[1] Niagara as used by the Survey includes all the limestones described in this report as "Niagara" and "Clinton," but in order to avoid confusion to the reader accustomed to the old nomenclature and because of the lack of established names for the subdivisions here recognized the use of the old names is continued in this report.

and cross-bedded layers. Bedding planes are more numerous than in the massive portions of the "Niagara," but the rock is denser and more insoluble and the bedding planes are less commonly developed as water passages, except near the base. Joints are very few in number. Altogether, the "Clinton" is a rather resistant rock and makes numerous abrupt scarps along the sides of many bluffs. (See Pl. VII, *B*, p. 45.)

RICHMOND AND MAYSVILLE FORMATIONS.

Taken together the beds of the Richmond and Maysville formations are about 550 feet thick and consist mainly of thin layers, 1 to 10 inches thick, of gray or bluish limestone, alternating with similar or somewhat greater thickness of soft bluish shales (Pl. VIII, *B*, p. 46). Both shales and limestones become yellow or brown by weathering. Outcrops near Cincinnati show a considerable thickness of rather fine shales at the top of the Maysville and at the base of the Richmond, but other parts of the formations are predominantly of limestone. Geologically the Richmond and Maysville can be divided, but considered as water bearers they are essentially a unit and are therefore generally treated together in this report. The distinction between them is seldom recognized in wells and they appear to carry water of the same general quality. The limestone layers abound in fossils that indicate the marine origin of the beds.

The Richmond and Maysville formations are far more extensive areally than any other formation in southwestern Ohio (see Pl. I), extending from the "Clinton" outcrop in Preble and Montgomery counties to Ohio River, and from central Greene, Clinton, and Highland counties to the Indiana line, thus constituting the surface rocks over the greater part of the region. They reach their highest elevation near their northern limit, where they stand as much as 975 feet above sea level. From this elevation they descend to less than 500 feet along the line where they cross the Ohio, in southeastern Clermont County. At Cincinnati their top is about 550 feet above sea level or 430 feet above the river.

EDEN AND UTICA SHALES.

The Eden shale consists of soft light and dark gray shales that weather yellow or brown on exposure. At the base of the Eden shale there are a few feet of drab shale representing the Utica shale. These two formations have a combined thickness of about 250 feet, nearly all of which belongs to the Eden shale. They are free from limestone, except for local layers in the Eden most of which are 1 to 4 inches thick and are separated by several feet of shale. They contain salt-water fossils, which indicate their marine origin. As the

Eden shale is among the lower formations, it outcrops only in the deep valley of the Ohio and in the lower portions of its tributaries (Pl. I). The upper part of the Eden surface near Cincinnati is about 720 feet above sea level and its bottom is 470 feet above sea level or 50 feet above lower water of the Ohio.

POINT PLEASANT FORMATION.

The term "Point Pleasant" is applied to the series of thin beds of alternating limestones and shales carrying true Trenton fossils and occurring immediately below the Utica shale in the vicinity of Cincinnati and along Ohio River both to the east and the west. At Cincinnati the Point Pleasant has a thickness of about 150 feet, but only 30 or 40 feet of this is above low-water mark, the top being considerably below the Ohio flood plain. The shales are dark-gray, hard, compact layers, 2 inches to a foot or more thick, and the limestones are impure grayish beds of about the same thickness. The heavier bedding and the more massive or compact character of the rock distinguish it from higher beds. It carries numerous marine fossils.

"BIRDSEYE" LIMESTONE.

The "Birdseye" limestone,[1] the so-called "Trenton" limestone of well drillers, is generally a massive, compact, grayish limestone, breaking with curved fractures, but at some points, as in the oil regions, it appears to be dolomitic and more or less porous in its upper part. In southwestern Ohio its total thickness is about 600 feet, but it does not outcrop, its upper part, or contact with the Point Pleasant formation, being about 100 feet below the level of Ohio River at Cincinnati.

During the oil and gas boom of 25 to 30 years ago many wells were sunk to the "Birdseye." From the data thus obtained the depth to the formation throughout the area became known and it was possible to construct a map (Pl. IV) showing by contours the elevation of its surface above sea level. Comparison with the elevation of the surface of the ground (see Pl. IV) gives the depth to the "Birdseye" at any particular point. The surface of the "Birds-

[1] Detailed investigations by E. O. Ulrich and others, made since the field work for the present report was completed, show that the geology beneath Cincinnati is far more complicated than has hitherto been supposed and that the elevation of the "Birdseye" limestone is considerably greater in the vicinity of the city, at least locally, than appears to be indicated by the structure contours of Plate IV. It is possible, if not probable, however, that the so-called "Trenton," upon which the structure contours are actually based, is not the top, but rather a lower and harder bed within the "Birdseye." If this is so, it will account in large measure for the discrepancies between the contours of the map and the elevations of the "Birdseye," as given in the text.

MAP OF SOUTHWESTERN OHIO, SHOWING ARTESIAN CONDITIONS
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eye" serves as a convenient reference horizon for other formations, notably for the water-bearing bed in the St. Peter sandstone below.

ST. PETER SANDSTONE.

The St. Peter sandstone in southwestern Ohio appears to be a shaly and calcareous, but more or less open, sandstone about 400 feet thick. It lies about 850 feet below the surface at Cincinnati, from which elevation it descends northward and eastward to a still greater depth before rising again. Its nearest outcrop is in southeastern Wisconsin, about 350 miles from Cincinnati. Eastward and southward it seems to thin out and disappear. Its porosity probably is due largely to the removal of the lime that originally filled the spaces between the sand grains.

CAMBRIAN AND ORDOVICIAN DOLOMITE.

The Cambrian and Ordovician dolomite lies, according to well records, about 1,225 feet below the surface at Cincinnati, its nearest outcrop being in the Appalachian region 200 miles southeast. It appears to be a buff, brownish, pink, or reddish dolomitic limestone or marble, possibly with a sporadic bed or two of shale. It was penetrated to a depth of about 1,000 feet by the well at the Moerlein brewery, but its bottom has never been reached. Observations in Tennessee lead to the belief that it is at least 3,000 feet thick.

STRUCTURE.

The part of southwestern Ohio herein discussed lies on the crest and flanks of what is known to geologists as the Cincinnati anticline. It is a broad rock arch or dome, the center of which is near Cincinnati. From it the rocks dip gently away to the east, north, and west, but rise to a still higher point in central Kentucky to the south. Nothing in the surface relief indicates the presence of this anticline, and it is recognized only by geologic studies. On Plate IV contour lines, or lines drawn through points of equal elevation, on the "Birdseye" limestone, as determined by well borings, are shown. Parallel to these contour lines the rock is horizontal, whereas at right angles it dips away at a rate indicated by the distance to the next contour, which is just 50 feet lower than the first. The rate varies from a little more than 10 feet to the mile near Miamisburg to about 3 feet to the mile in western Hamilton County and near Dayton. The contours also bring out the fact that the dome is not entirely regular but is marked by a crease of steeper dips along a line from Dayton to Hamilton.

UNDERGROUND WATERS.

RELATION TO SURFACE FEATURES.

So intimate is the relation of underground water to surface features that in many places the former may be said to be largely controlled by the latter. Thus, the amount of water absorbed depends to a large extent on the slope of the catchment surface; the direction and rate of movement of underground waters, especially of the shallower waters, depend largely on the direction and slope of the surface; the shape of the water table conforms in general to the surface configuration; the leakage from water-bearing beds as a rule depends on the cutting of the beds by depressions of the surface; and the depth, head, volume, and many other factors are materially affected or controlled by the character of the land surface. The study of surface features is therefore of great importance in all underground water investigation.

In southwestern Ohio, where the plateau constitutes the greater part of the surface, it is naturally an important source of ground water, the occurrence of which is intimately related to the nature of the surface formation, whether this be drift or rock, to the width of the plateau remnants where cut by valleys and ravines, and to the nearness of the bluffs at its edges.

On the sharp and narrow crests between the ravines the rainfall is quickly shed to each side, very little soaking into the ground; and even the small amount absorbed drains rapidly from the narrow ridges, leaving them little or no ground water above the level of the valley bottoms.

For similar reasons the amount of ground water decreases toward the edges of the valleys. A few miles back from these borders, especially in the flatter portions, ground water usually lies very near the surface, often rising in wet seasons within 5 feet of the top; but as the valley is approached the water level becomes much lower, until near the edge no water whatever may be found within reach of ordinary wells, both soils and rocks being completely drained.

Though the above generalizations are true throughout the area, whatever the nature of the deposits, the shortage of water is much more marked in certain types of materials. Where the surface materials are loose and porous sands and gravels the loss of the water is much more rapid than where they are pebbly clays and other relatively impervious materials. Likewise the loss is greatest in porous rocks and in those which, like the limestones, have numerous bedding planes and small solution passages that permit the ready escape of the water, and is least in impervious shales.

Although on account of their small area the valleys are not the most common source of ground water in southwestern Ohio, they are

in many ways the most important, as they furnish supplies not only for three-fourths of the waterworks in the region, but for most of the manufacturing plants as well. The abundance of water is due to several causes. As the valleys are much lower than the surrounding hills they form natural lines of drainage, toward which the water in the rocks, as well as that upon the surface, moves. The water falling on the hillsides likewise finds its way to the valleys and is added to the supply. The main reason for the importance of the valleys as a source of water, however, arises from the gravel and sand with which the larger ones are filled to considerable depths; these materials, which have porosities of 25 to 40 per cent, hold immense quantities of water, which is readily given up to wells.

SOURCE.

POPULAR CONCEPTIONS.

In view of the number of different popular conceptions as to the source of the underground waters in southwestern Ohio a few words on the subject may not be out of place. In this, as in other regions in Ohio and in the upper Mississippi Valley, it is a common belief that the waters are derived through subterranean passages from the Great Lakes. The level of Lake Michigan is 581 feet, which is only 75 feet above Cincinnati, and with the exception of a few of the valleys is several hundred feet below the general level of this part of Ohio. The elevation alone, therefore, precludes such a source for the waters.

Along the Ohio another view, namely, that the ground water is derived from the river, is widely held by the people, who have long noted that in many places only the wells at or near river level procure water. Careful studies of the ground waters, however, have shown that they move in a manner similar to surface waters; that is, from the hills toward the valleys, and join the streams or underground flows in the latter just as surely as the tributary joins the master surface stream. When the river rises it backs up both the surface streams and the ground waters, which explains the fluctuations in ground-water level. Only when sudden floods lift the river faster than the ground water can come in do movements away from the river take place. Even then the water does not penetrate far inland.

LOCAL SOURCES.

The independence of the ground waters, even when near the river, is indicated by their composition, which is almost always quite different from that of the surface waters, the ground waters usually carry-

ing very much larger quantities of mineral matter than the river water. Wells only 20 feet from the bank, if lightly pumped, will ordinarily draw from the ground water rather than the river, and wells sunk considerably below the river bed are even less likely to draw from the stream. If the wells are heavily pumped, however, river water may be drawn in. The nature of the ground-water movements and the reason why wells adjacent to rivers seldom get river waters is shown by figure 2.

Most of the ground water in valleys percolates from the surrounding hills, working its way downward through joints or fissures and

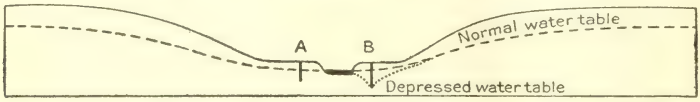


FIGURE 2.—Cross-section showing ground-water conditions in valleys. A, lightly pumped well not getting any of its water from the river; B, heavily pumped well securing more or less river water.

outward along bedding planes or other partings. That coming from below is relatively small in amount. On the hilltops the water is mainly derived directly from the rainfall and represents the portion not yet absorbed by the deeper rocks.

GENERAL SOURCES.

The water of the deeper rocks in southwestern Ohio is derived mainly in one or the other of two ways: (1) By absorption at their outcrops, and (2) by penetration downward through joints.

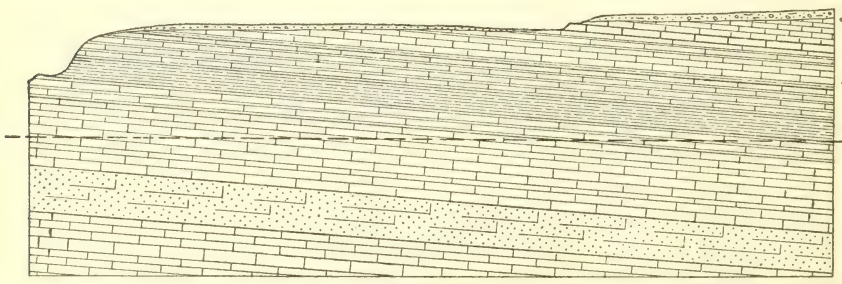


FIGURE 3.—Geologic cross-section of southwestern Ohio. *a*, Cambrian and Ordovician dolomite; *b*, St. Peter sandstone; *c*, "Birdseye" limestone (so-called "Trenton" of well drillers); *d*, Point Pleasant formation (Trenton fossils); *e*, Eden shale (including at base a small thickness of Utica shale); *f*, Maysville formation; *g*, Richmond formation; *h*, "Clinton" limestone; *i*, "Niagara" limestone; *j*, till. Dotted line indicates sea level.

From the geologic cross section (fig. 3) it is seen that the conditions of outcrop vary considerably. The "Niagara" limestone, which is the best water-bearing formation in the area, has a broad flat outcrop presenting abundant opportunity for the absorption of water from the overlying coating of drift materials, which serves as an admirable feeder. The "Clinton," because of its hardness, not uncom-

monly forms steep slopes or scarps (Pl. VII, *B*, p. 45) at its outcrop, making the absorption of water from the outcrop very difficult, especially as the drift "feeder" is in many places thin or absent. The limestones and shales of the Richmond and Maysville formations have very favorable catchment conditions, the outcrop being both level and covered for the most part by a drift "feeder," but unfortunately these formations contain enough shale to greatly hinder the circulation of water. Moreover, the lower part of the Maysville formation outcrops mainly on the steep bluffs of the Ohio and of its larger tributaries and thus has little chance to absorb water. The Eden shale likewise outcrops mainly in steep cliffs, which fact, taken in connection with the prevailing shaly character, effectually keeps out the water, making the formation the poorest water bearer in the district. Only the upper part of the Point Pleasant formation outcrops in the region, but, owing to the solubility of the limstone layers, it absorbs considerable water locally. These rocks outcrop farther south in Kentucky, but it is doubtful whether any of the water which

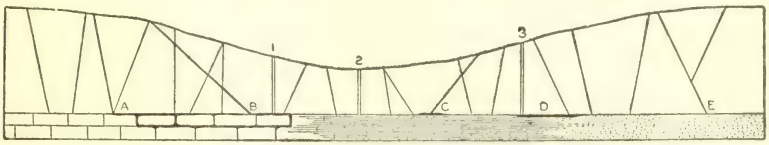


FIGURE 4.—Section illustrating the feeding of water beds through joints (water-bearing joints indicated by the heavier lines). A, B, Water horizon between limestone and compact, jointed rock fed by joints at A and B; C, water horizon between shale and compact jointed rocks with local circulation only; D, water horizon fed from sandstone bed; E, sandstone bed fed by joints; 1, flowing well from bedding plane between limestone and compact jointed rocks; 2, dry hole (no circulation along bedding plane); 3, flowing well from bedding plane fed from sandstone.

they contain in southwestern Ohio comes from this source. The "Birdseye" limestone does not outcrop in Ohio, but does outcrop over an extensive area in central Kentucky. Being locally rather soluble it is possible that some of the water may penetrate from the outcrop. The St. Peter sandstone does not appear at the surface anywhere to the south or east, apparently thinning out in these directions. To the north it comes to the surface in southern Wisconsin, about 350 miles from Cincinnati, where it has an elevation of about 800 or 900 feet. In view of the large volume of water which it contains, and of the thick covering of overlying beds, it seems likely that much of its supply is derived from the distant outcrop.

Besides the water which enters at the outcrop, much undoubtedly penetrates to the underlying beds through joints, as is shown diagrammatically in figure 4, in which A and B represent joints feeding a limestone furnishing water to well 1; C, a joint feeding a local bedding plane; D, a bedding plane connecting with sandstone fed by joint E and furnishing water to well 3.

It is probable that the water which so abounds at the top of the "Clinton" limestone reaches it in part through joints in the "Niagara" beds, as at A and B in the figure. Some water may reach the top of the Eden shale through joints in the Richmond and Maysville formations, but because of the insoluble character of the rocks the circulation is very slight, as at C in the figure. It is also barely possible that some of the water of the St. Peter may reach it through joints, but the amount so derived is probably very small.

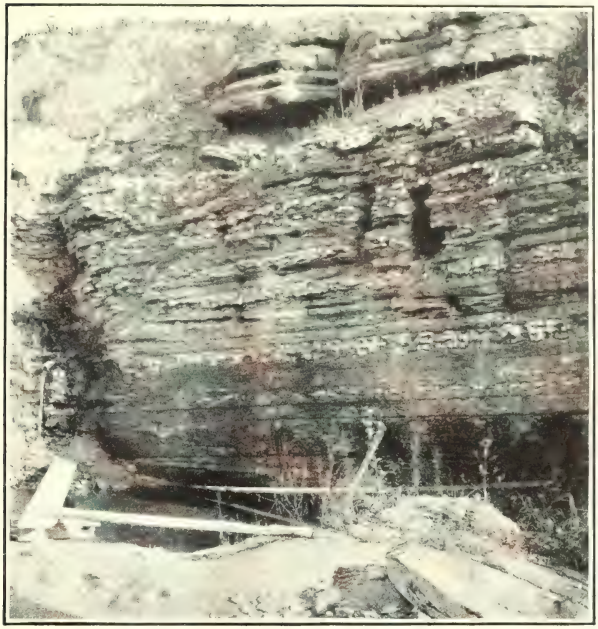
OCCURRENCE.

Waters in rock.—The underground waters derived in the several ways outlined above occur in the rocks under many conditions. In absolute amount that in the pores or spaces between the particles which make up the rock is probably greatest, but unfortunately in many of the finer-grained rocks the water in the pores, though abundant, is so firmly held that little or none of it is yielded to wells. In southwestern Ohio the St. Peter sandstone is the only formation that yields large amounts of water from the pores of the rock itself, the other formations giving it up only when it occurs along joints, bedding planes, solution passages, or similar openings.

Joints are smooth fracture planes cutting the rock in different directions. In limestone the joint openings are at first hardly appreciable, but as the waters work their way downward they gradually dissolve mineral matter from the walls, widening the joints until the water moves freely. Such a joint in the "Niagara" limestone is shown in Plate V, *A*. So universal is circulation of this type that a joint is rarely found which does not possess solution features or iron-stained walls that give evidence of the passage of water.

Bedding planes are even more important as water bearers than are the joints, for the water seeps along them at many points. The bedding planes, like the joints, are at first not generally actual openings; they simply represent lines along which the water percolates by reason of imperfect adhesion between layers of different texture or different materials. Under the action of the waters, however, they rapidly widen and afford passage for large amounts of water. The openings differ, however, from those of the joints. Instead of forming an open crack the waters dissolve a complicated system of meandering passages, such as those shown in Plate V, *B*, which represents a bedding plane in the Maysville formation.

As the joints and bedding planes become wider the water tends to concentrate along certain lines, forming solution passages, many of which are of considerable size. Plate V, *A*, shows a spring issuing from such a passage, which was uncovered and traced for a long distance during the process of quarrying. Plate VI, *A* (p. 44), shows another solution opening in the same quarry.



A. LARGE SOLUTION CHANNELS IN NIAGARA LIMESTONE.
Due to enlargement of vertical joints. Spring issues from bedding plane on left.

B. RAMIFYING SOLUTION CHANNELS ALONG BEDDING PLANE IN MAYSVILLE FORMATION.
Showing circulation of rock waters. About one-fourth natural size.

Waters in drift.—The drift includes the local irregular gravelly heaps and ridges and the pebbly clay or till which overlie the rocks of most of the area (Pl. II). The clay is not the ordinary compact, impervious, water-laid clay, but carries in places more or less sand and pebbles, which are either irregularly distributed through the mass, converting it into a heterogeneous mixture, or form more or less well-defined sandy or gravelly layers. Nearly everywhere it contains considerable water, even in its more clayey portions, in much of which the water gathers into little tubular channels, as well as saturating the more porous sandy or gravelly portions. The drift not only directly supplies important amounts of water, but also serves as a feeder to the underlying rocks, which will absorb more water from it than if they were exposed directly to the rain.

The more gravelly drift in the ridges contains little water, except in the very lowest parts, because of the ease with which it drains out from the open porous material.

Waters in alluvium, etc.—All the larger stream valleys and many of the smaller ones contain considerable depths of clays, alternating with more open sands and gravels that hold great quantities of water and afford excellent supplies to many towns and to numerous

FIGURE 5.—Section showing valley alluvium fed from bedding planes and solution passages. A, Bedding plane, feeding alluvium with water derived from joint 1; B, joint feeding alluvium with water from joint 2; C, solution passage feeding alluvium.

manufacturing establishments. Nearly all of this water enters from the higher lands bordering the valleys and joins the underflow by seepages from bedding planes and by flows from joint planes and solution passages (see fig. 5). Analogous conditions probably exist at hundreds of points along nearly every stream in the region.

HEAD.

Many of the wells on low ground, both those in rock and those in the alluvial fillings of the valleys, yield flowing water, and nearly everywhere the water is under artesian pressure, rising very materially when encountered. The pressure, though depending on certain general principles, differs considerably with the different materials in which the water is contained and with the different degrees of confinement to which it is subjected.

Waters in rock.—Water contained in rocks may be either unconfined, in the upper weathered portion of the rock masses, or it may lie deep and be confined under pressure in pores, joints, bedding planes, or solution passages.

In deep confined waters the head is dependent on the factors that control the entrance of the water. Entering at the outcrop of sloping rocks, such as those of southwestern Ohio (fig. 3, p. 34) the water passes gradually downward under the action of gravity, is prevented from escape by overlying more or less impervious beds, and fills all the openings and pores which it can reach. As the beds are filled the water in their lower part is subjected to the pressure of the overlying water, and, when reached by a well, will rise in proportion to the height of the water level in the higher portion of the bed, giving, if the surface is low enough, an artesian flow.

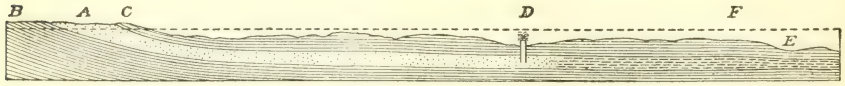


FIGURE 6.—Section showing conditions of flow in inclined porous bed, becoming thinner. *A*, Porous bed between impervious beds *B* and *C*, thinning out at *E*, thus furnishing conditions for flow at *D*, but not at *F*. Applied to the St. Peter sandstone, *A* would represent its Wisconsin outcrop, *D* the flowing wells at Cincinnati, and *E* its termination somewhere to the south or east.

The underground conditions controlling such flows differ considerably, some of the simplest being shown by figures 6 and 7, in which the water is represented as occurring in porous beds. In reality none of the beds in southwestern Ohio except the St. Peter sandstone is porous in the ordinary sense of the word, and the water really occurs in joints, solution passages, and bedding planes, in which the head depends on the source of the water and the conditions of retention. Where the opening drains freely into some valley or other depression the water may flow through the subterranean passages as does the

FIGURE 7.—Section showing conditions of flow in inclined porous bed, becoming impervious. *A*, Porous bed between impervious beds *B* and *C*, grading into nonporous bed at *E*, the confinement giving rise to a flow at *D* but not at *F*.

water of a surface stream over its bed, but where no ready escape offers the water accumulates, as in the porous beds previously described, subjecting the lower part to considerable pressure, whose degree varies with the level of the surface of the confined water.

Waters in drift.—In general the drift surface has a considerable slope from north to south, its elevation declining from 1,100 feet near its northern limit to about 800 feet at its southern border. As already explained it is characterized by numerous passages or porous layers, many of which appear to slope in the same direction as the surface. It therefore occasionally happens that the pressure transmitted in such passages from some higher point farther north is sufficient to lift the water to the surface even on the flat plains, and flowing wells

result, as near Brookville in Montgomery County. The conditions are still more favorable in valleys or other depressions in the drift, in which flows are even more numerous.

Waters in alluvium, etc.—The head of the waters in the valleys is due to at least two different causes, one of which is the pressure transmitted from higher points farther upstream, and the other the pressure derived from the passages and lamination planes where the valley bottom is in drift or from joints, bedding planes, and solution passages where it is in rock. In order to obtain a flow from upstream pressure the water must have free entrance upstream, and must be prevented from rising downstream by some clayey or other more or less impervious layer. A similar cover must be present to give a flow when the alluvium is fed from the rocks. Unfortunately such a cover is lacking in many localities or is too imperfect to confine the water, which escapes upward and joins the streams. It is because of this fact that flows are not more common in valleys.

SUPPLY.

By available water is meant that portion of the ground water which can be economically obtained by man. It does not include the amount held in the microscopic pores of the compact rocks and never yielded to wells in appreciable quantities, even though it may be present in amounts greater than the free water.

Of the different materials in the region the drift and alluvium hold the largest percentages of available water. In the drift the amount probably varies from about 5 per cent in the clayey portions to 30 per cent or more in the more sandy or gravelly portions, the average probably being fully 15 per cent of the volume of the drift; that is, a saturated layer 100 feet thick contains the equivalent of a 15-foot layer of water. In alluvium sandy materials generally predominate, the average porosity being probably at least 20 or 25 per cent.

In the solid rocks the percentage of water is generally less. Of the limestones the "Niagara" and "Clinton" carry the most water, but even in these it is doubtful if the free water in a bed 100 feet thick would make a layer more than a foot deep. In the shaly limestones the amount is still less, there probably being not more than one-eighth or one-fourth as much as in the "Niagara," and in the shales the amount of free water is so small as to be practically negligible. In the deeper limestones, such as the "Birdseye," the aggregate amount is considerable, but probably would not aggregate more than a few inches to each hundred feet, and in the still deeper Cambro and Ordovician dolomite the amount is very small indeed. The St. Peter sandstone is an exception among the rocks of the

region, for it probably carries at least 10 to 15 per cent of water, containing in its thickness of approximately 400 feet the equivalent of a 40 to 60 foot layer of water.

Exclusive of the water of the St. Peter sandstone, which is too high in sulphur for ordinary use, and the water of the "Birdseye" limestone, which is very generally salty, by far the greater part of the water occurs either in the drift and alluvium or in the "Niagara" and "Clinton" limestones, both of which are at or near the surface in this area are easily reached in shallow wells. Rock wells that go below the level of the "Clinton" limestone have rather small chances of success, although a few obtain satisfactory supplies; the majority either fail entirely or get supplies too small for ordinary uses. Deep wells give no promise, for though in most places they can obtain water, it will generally be either salty or highly charged with sulphur.

WATER-BEARING FORMATIONS.

Practically all rocks contain more or less water, and differ only in the degree of their saturation. Those containing water in only small amounts may play an important part as confining beds and must be considered in any discussion of the water. The several formations recognized in southwestern Ohio and their water-bearing capacities are considered below.

UNCONSOLIDATED DEPOSITS.

ALLUVIUM AND GLACIAL VALLEY FILLING.

Most of the water of the alluvium and of the interbedded glacial deposits works its way downward from the surrounding highlands by seepage from bedding planes, along solution passages or through joints in the rocks in which the valley is cut. Occasionally, as during floods, when the water in the stream rises faster than that in the ground, the flow may be reversed and river water may penetrate the alluvium on each side or may even force its way downward. As a rule, however, as is shown by the greater hardness of the water in the alluvium as compared with the river water, the alluvium contains chiefly the more mineralized waters from the rock hills. It also derives water directly from the rain that falls on its surface.

Ordinarily the alluvium is sufficiently permeable to permit water to percolate through its entire body, which, in fact, is always saturated below the water level of the stream. In severe droughts the water level in the smaller and more steeply sloping valleys sinks below the level of the stream bed, and the channels, except perhaps for a pool here and there, become dry. In most valleys, however, the water level is not far below the surface and there is considerable

underflow. All the water occurs in the pores or openings between the grains, the amount so held usually varying from 25 to 35 per cent of the bulk, according to the nature of the material.

Although the alluvium is generally saturated with water below the level of the stream, all of this is not available for wells. Clayey materials, although perhaps containing 40 per cent of their bulk of water, hold it so firmly that little or none is given up to wells, and even sands do not yield all that they hold. In general, however, the sands and gravels yield their water freely, and in order to procure an abundant supply a well need only find a bed of material thick enough to permit the insertion of a sufficient length of strainer that is coarse enough to prevent the grains from passing through the screen. In most valleys such beds can be easily found, especially in the center, but in some the requisite sands or gravels are absent near the margins and the wells are failures.

TERRACE GRAVELS.

The water in the terrace gravels, like that in the alluvium, is derived from the rocks forming the valley walls, from rainfall on the terrace surfaces, and occasionally from backwater of the flooded streams, seepage from the valley walls being the principal source of the water in both the gravels and the alluvium. Waters derived directly from the rainfall are collected by the layers of cemented rock and do not immediately join the ground-water body; hence they are less important as a source of supply in the terrace gravels than in the alluvium.

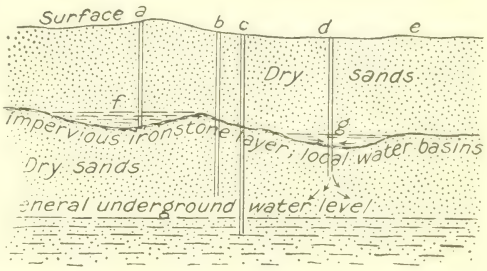


FIGURE 8.—Diagram showing occurrence of water in terrace sands and gravels. *a*, Well obtaining water from local water-bearing basin at *f*; *b*, well missing local basin and stopping short of general water level; *c*, well missing local basin, but obtaining water from general supply; *d*, well reaching local basin *g*, but penetrating its impervious underlying layer and permitting the water to escape.

As already indicated, the terrace materials are generally open and porous, permitting the water, especially in the smaller terraces, to drain rapidly away, leaving only small supplies above the general ground-water level of the valley. In the broader terraces, such as those north of Cincinnati, the water may be held back by the friction of the sand and gravel and may stand considerably higher than it does near the stream. Where cemented layers (Pl. VI, *B*) have been found local water pockets commonly occur in depressions in the upper surface (fig. 8), a fact also true to a less extent of the clay layers.

Because of the ease with which the water drains from the gravels wells must generally be sunk to the level of the stream in the adjacent valleys before they reach supplies (fig. 8, *c*). A few wells draw supplies from pockets in the surface of the cement or ironstone layers (fig. 8, *a*), but many fail to strike such pockets (fig. 8, *b*), and others penetrate too far and lose all supplies (fig. 8, *d*). Clay or till layers collect the water in a similar way and some of them afford supplies to wells.

LOESS.

The principal source of the water of the loess is rainfall, and the water of the loess of the flat upland crests is derived solely from this source. On the hillsides and benches, however, especially where the loess rests directly on the rock, some water doubtless percolates laterally into it from the rocks against which it rests.

The water occupies the pores of the silt itself, there being no joints or other openings. Owing to the fineness of the silt the water ordinarily does not readily drain away, but is held in the material, especially where it rests on rock or other relatively impervious substance. Where the loess is thin and is underlain by porous beds it generally contains no water. Where it is thick it commonly yields moderate supplies of water to shallow wells, especially where it rests on an impervious substratum of rock or clay, but, except near the Ohio, it is generally only a few feet thick and wells go through it into the underlying materials. It is not a satisfactory source of water in southwestern Ohio, but in a few places it furnishes enough for stock.

MORAINAL DRIFT.

The moraines are commonly the highest deposits in the region and hence are fed almost entirely by rainfall. Where they are banked against the valley sides, however, considerable water may enter them from the rock or drift in which the valley is cut.

The moraines are commonly open and porous and the water drains out from them very readily, little usually remaining above the impervious till sheet or rock on which they rest. Where till is present, however, in the body of the moraine, the water may be held in local layers or pockets considerably above the base and in a few places may be confined under artesian pressure.

Because of the free drainage few shallow wells obtain water from the moraines, although some find a little on top of or within the clay or till layers or at the contact of the main till sheet below. Commonly, however, the wells have to penetrate the underlying till to a considerable depth before getting adequate supplies.

TILL.

As the till for the most part occupies the highest levels, it derives most of its water directly from rainfall, few rocks being in a position to yield water to it, but some of the till that lies in old buried valleys doubtless derives water from the rocks. The contact of the "Niagara" and underlying "Clinton" limestone is everywhere a strong spring horizon and considerable water must pass into the drift where it covers the contact.

The clayey portion of the till, like practically all other fine material, undoubtedly contains considerable water in its pores. In fact, the larger part of its water is so held. It includes, however, many gravel or sand layers, due either to water action contemporaneous with the ice or to the subsequent removal of the fine silt which filled the spaces between the pebbles of gravelly till layers. The openings so formed are practically everywhere saturated with water, as are the small more or less tubular openings found in the clay itself. Both the gravel layers and the tubular passages in general have a distinct slope, and where the point of emergence is at some distance or the passage of the water is obstructed in any way considerable artesian pressure may be developed.

The water movement through the till is very slow, owing to the friction, and drainage takes place only with difficulty. As a result the water level stands very high, in many places within a few feet of the surface, especially where this is unbroken by near-by valleys. Even on narrow ridges much water is retained by the more clayey types of till.

The waters in the more clayey portions of the till are given up with difficulty, although enough will usually seep into a dug well to supply household demands. For stock, however, it is often necessary to go to considerable depth. To supply a driven or drilled well, a gravelly or sandy layer or a definite bed of sand or gravel must be tapped. Where the drift is deep such a layer can usually be found, especially over a buried valley, and in some places, as in the vicinity of Brookfield, flowing wells may be obtained. In general it may be said that there are few districts where the till is 30 feet or more thick where water can not be obtained in amounts ample for domestic and farm purposes. The great difficulty in such deposits is that it is frequently too easy to get water, especially in wet seasons. Many diggers stop at 10 or 12 feet and then see their wells fail in the first dry season, when a 25 to 40 foot well would have carried them through any ordinary period of drought.

OLD GRAVELS.

The waters of these old sands and gravels are nearly all derived from the overlying loess and till, which in turn are fed mainly by

rainfall. Possibly a small amount may come from the rocks where the materials lie against the higher crests.

The water occurs in the pores of the sands and gravels and is not under pressure, for the beds, though overlain by relatively impervious till, are too flat for the development of artesian head.

The materials are everywhere reached by shallow wells, which generally obtain sufficient supplies for domestic uses within 15 feet of the surface.

ROCK FORMATIONS.

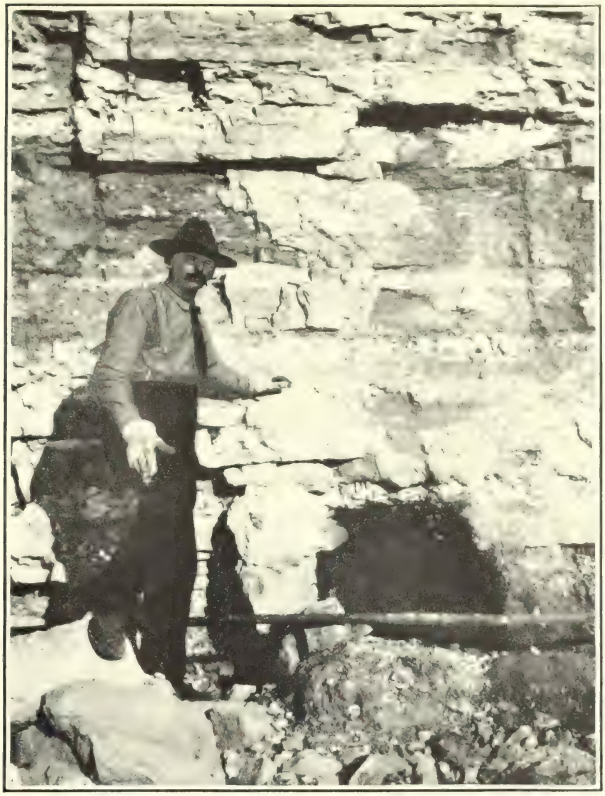
"NIAGARA" LIMESTONE.[1]

At a few localities, as at Limestone City, southwest of Springfield, the "Niagara" limestone lies very near the surface and may absorb considerable water directly from the rainfall. Throughout the greater part of the area, however, the "Niagara" is overlain by thick deposits of drift. On the uplands this drift is mainly till, but in the valleys much of it is stratified. The till is the main source of supply, being saturated with water (p. 43), which it constantly feeds to the underlying limestone. Little water probably enters the rock from the valley drift, as the movement is normally toward and not away from the valley.

The limestone, because of its general granular and open character, is commonly very soluble and permits the ready formation of water passages, especially in the weathered portion near the surface, where it is in some places almost honeycombed with openings (Pl. VI, *A*). Considerable water passes along the joints, which locally become enlarged into open passages (Pl. V, *A*, p. 36), and much flows along the bedding planes. The water generally works its way downward to the base of the formation, where it collects along the contact with the underlying more insoluble "Clinton" limestone, and passes laterally toward the outcrop of the beds in the valleys or elsewhere. A similar concentration also occurs along a number of the shale layers in the limestone.

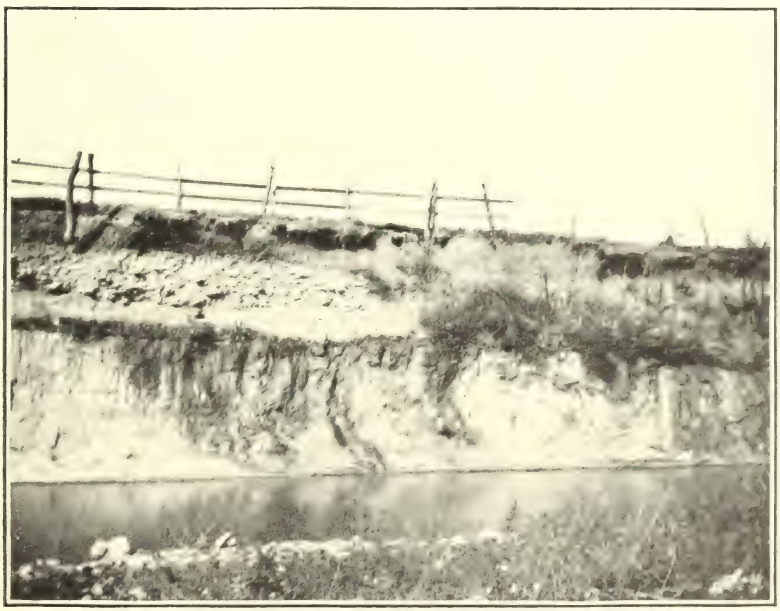
Usually, if there is a considerable thickness of the limestone and the boring is not too near an outcropping edge from which the water can readily drain, a well will procure water if carried to one of the shale layers or to the base of the limestone, where, as pointed out above, the water has a tendency to collect. In many places, however, it will not be necessary to go to this depth, wells generally procuring supplies from the upper weathered portion wherever there is any considerable coating of till to serve as a feeder. Some of the deep wells also obtain water from isolated joints, bedding planes,

[1] See footnote, p. 22.



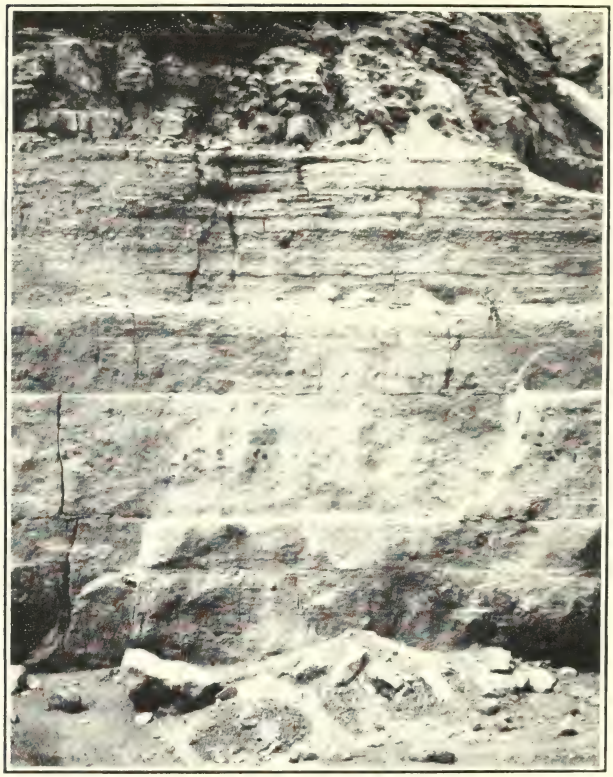
A. LARGE SOLUTION OPENING IN NIAGARA LIMESTONE.

Due to enlargement of bedding plane. Openings of this type afford important supplies to wells.



B. CEMENT-ROCK LAYER IN TERRACE GRAVEL.

Such layers may collect water and afford supplies to wells.



A. NIAGARA LIMESTONE.

Showing development of partings capable of carrying water in upper portion due to weathering, while lower, unweathered portion remains dense and massive.

B. CLINTON LIMESTONE.

Showing cliff character of outcrop and spring formed by waters collecting on an upper impervious layer.

and solution passages at levels intermediate between the top and bottom layers, but such openings are comparatively few in number and are often missed. In general, the "Niagara" limestone is a fairly reliable water bearer where it forms the bedrock and is overlain by till.

"CLINTON" LIMESTONE.[1]

The water of the "Clinton" limestone is derived mainly from the "Niagara" limestone, which overlies it in most localities and which conducts the water downward to it through joints and solution passages (p. 44). In some places near the outcropping edges of the formation the "Niagara" is absent and the saturated till rests directly upon the surface of the "Clinton," acting as an efficient feeder. The uncovered outcrops occur mainly in vertical bluffs, into which no rain can penetrate, but some doubtless directly enters the limestone where it is only thinly covered by soil, as it may be locally for some distance immediately back from the bluffs (Pl. VII, *B*).

The "Clinton" limestone usually contains some water in solution passages or in enlarged joint or bedding planes, especially in its basal portion. The value of the "Clinton" as a water bed depends chiefly on its action in collecting water from the overlying "Niagara" and conducting it along the contact to the nearest outcrop, where it emerges as springs (Pl. VII, *B*). So numerous are the springs at this contact that in many places they serve to show the position of the beds, it being not uncommon to see a line of seeps encircling a hillside at the "Clinton" horizon, even where the rock itself is covered with a considerable thickness of drift. In fact, the "Niagara" and "Clinton" contact is the chief spring horizon in the region.

The "Clinton" limestone, through the springs to which it gives rise, furnishes abundant supplies to many farms and even to some towns, and where it lies within the reach of surface weathering it may yield supplies to numerous shallow wells. Wells also encounter water passages within the rock itself, and especially at its base, obtaining from it a considerable supply.

RICHMOND AND MAYSVILLE FORMATIONS.

Over most of their extent in southwestern Ohio the Richmond and Maysville formations are covered with thick deposits of drift, consisting of till in the uplands and stratified gravel in the valleys. The till, which is generally saturated in its lower portion, is their principal water feeder, little entering them from the valley deposits, toward rather than away from which the ground water is moving. Considerable water also enters these formations from the loess in

[1] See footnote, p. 22.

the areas beyond the till boundary (Pl. II), and small amounts are derived directly from the rainfall on the bare exposures on some of the hillsides. Where the beds are overlain by the "Clinton" limestone the water generally enters at their outcropping edges, seeping down from the overlying till. Little, if any, water probably enters through the "Clinton," except possibly where the limestone is cut by joints.

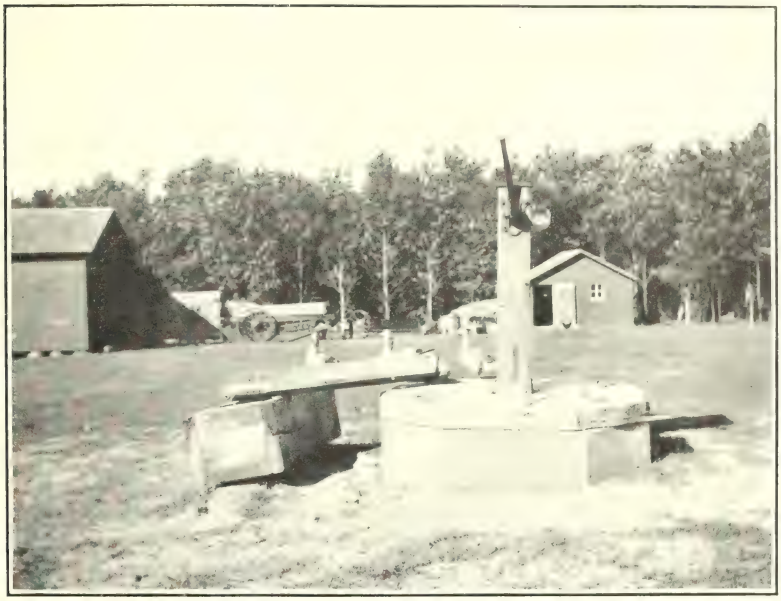
The water occurs in the Richmond and Maysville formations in several ways. Some doubtless percolates along the partings between the numerous laminæ of shale, some occurs in joints, and some appears along the bedding planes, marking the contact of limestone and shale layers. The water passing along this contact follows the top of the insoluble shale and gradually dissolves ramifying passages in the under surface of the overlying limestone. (See Pl. V, *B*, p. 36.) The size of the passages is generally limited by the thickness of the limestone beds, which is commonly from 1 to 10 inches (Pl. VIII, *B*), and also by the extent of the soluble layers, many of which are lenses inclosed above and below by shale or by layers grading laterally into shale. For these reasons water passages are neither numerous nor large.

As the Richmond and Maysville formations consist of alternate layers of shale and limestone, and as the shale readily crumbles on exposure and the limestone is dissolved by percolating waters, the beds disintegrate rapidly under the action of the weather, forming loose, porous masses which, under certain conditions, yield to open wells supplies sufficient for ordinary domestic and farm uses, especially on the broad flat crests, where the disintegrated rock is covered by 10 or 15 feet of loess and till. On the hillsides many wells fail to get satisfactory supplies because of the ease with which the water drains from the loose rock. Many wells sunk where the rock is very near the surface or on top of the sharp-crested ridges are likewise unsuccessful.

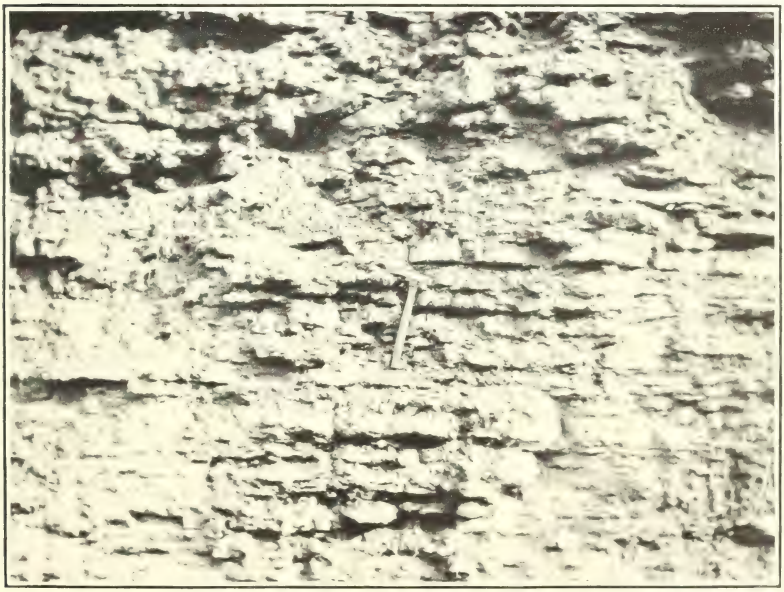
Most of the deeper wells, which penetrate below the weathered portion of the rock, obtain very small supplies and many fail entirely. The water of some is brackish from salt which it has dissolved during its slow circulation through the rock. A few wells obtain moderate supplies. The difference in the yield from well to well is due to differences in the size and distribution of the solution openings. A few wells encounter such openings and get supplies, but most of the wells fail to find them.

EDEN AND UTICA SHALES.

The disintegrated portion of the Eden shale derives most of its water directly or indirectly from rainfalls, the indirect supply passing through talus which has slipped down from overlying rocks to



A. WELL PROTECTED BY CEMENT CURB AND PLATFORM.



B. RICHMOND AND MAYSVILLE FORMATIONS.

Showing alternations of shale and limestone. The close spacing of the shale prevents the formation of large solution passages.

cover the outcrop of the shale. Where the shale lies beneath other rocks the water may reach it through joints connecting with the surface or with higher water-bearing beds, or it may penetrate along bedding partings or other openings. Besides the water in the disintegrated and weathered outcrops, the Eden and Utica doubtless carry small amounts in shaly partings or joints. Water also penetrates along the more soluble limestone layers but usually does not reach very far from the outcrop.

Except in their disintegrated superficial portion practically no supplies can be obtained from the Eden and Utica shales, the small amounts they contain being so held that practically none is given up to wells. Few if any drilled wells in these rocks yield supplies in southwestern Ohio.

POINT PLEASANT FORMATION.

The Point Pleasant formation outcrops in southwestern Ohio only along the banks of Ohio River, where it is generally covered with clayey or sandy silts, and it is entirely submerged at times of high water. In general (see p. 33), the movement of ground water, like the movement of surface waters, is toward and not away from the streams, and during normal stages of the river little or no water is absorbed by the rocks from the stream. During sudden floods, however, the river rises more rapidly than the ground water and then the river water doubtless backs up into the openings in the rock.

The Point Pleasant formation, or its equivalent, although outcropping in southwestern Ohio only along the river, comes to the surface farther south in Kentucky, where it doubtless absorbs considerable quantities of water, a part of which may even reach the Ohio. Small amounts also probably reach it through joints in the overlying rocks.

The water occurs mainly in meandering passages dissolved out of the limestone layers along their contact with impervious shaly beds. These passages commonly form a network, although some larger isolated passages occur. As the Kentucky outcrop is considerably higher than that in the Ohio Valley, the water may be under pressure sufficient to lift it considerably above the level at which it is encountered. Small amounts of water may also occur in joints.

Owing to the facts that the Point Pleasant is the country rock only in the Ohio Valley, and that even there it is overlain by flood-plain deposits carrying much larger quantities of water, it is seldom looked to as a source of water supply in southwestern Ohio, except where, as at Cincinnati, the demands are such as to necessitate the utilization of every possible source. Moreover, although it contains considerable quantities in the aggregate, the distribution of water in it is not only irregular and uncertain but is likely to be brackish, especially at

a distance from the river. For these reasons and because of its considerable depth beneath the uplands this formation is not a promising source of supply.

"BIRDSEYE" LIMESTONE.

The "Birdseye" limestone outcrops in north-central Kentucky in the valley of Kentucky River and other streams 60 to 90 miles south of Cincinnati. Though exposed only in the valley bottoms, it probably absorbs considerable water, which penetrates downward to the north along the more soluble layers of the limestone. More or less water also probably reaches the rock through joints connecting with the surface or overlying water beds.

The water seems to occur mainly along open passages dissolved in the more soluble portions of the limestone or along joint or bedding planes. As there are few shale partings to limit the size of the openings, many of them are several inches or more in diameter; they are often recognized in drilling by the "dropping of the drill." Some of these passages have been encountered in central Ohio as much as 1,000 feet below the surface, and fragments showing solution action have been brought up, indicating a rather free circulation at some time in the past.

Most wells penetrating the "Birdseye" limestone to the bottom find water that is under considerable pressure and that rises somewhat when reached. Unfortunately, however, it is not only exceedingly hard but is generally more or less salty and is unfit for drinking or for boiler or industrial uses.

ST. PETER SANDSTONE.

It is believed that a large part of the abundant supply carried by the St. Peter sandstone has been derived from its Wisconsin outcrop, inasmuch as the head and volume is far greater than would be expected if the water were fed through the overlying "Birdseye" limestone.

The water occurs in the pores of the rock, occupying spaces that were either never filled by the lime cement or that were formed by the subsequent solution of the lime. These must be rather large, as sufficient head is transmitted from the outcrop, 350 miles away and approximately 850 feet in elevation, to lift the water to about 600 feet at Cincinnati, a very moderate loss considering the distance. The rock is not everywhere saturated, however, and wells must penetrate it for some 300 feet to obtain the best supplies.

Abundant water is generally obtained from the St. Peter sandstone when encountered by wells, and flows are obtained when the altitude is not over 600 feet above sea level. The many flowing wells at Cincinnati obtain their water from this formation. The main supply

is found about 300 feet below the top of the bed, or 1,200 to 1,300 feet below the surface at Cincinnati, and the flows are not materially increased by going deeper. (See Pl. IV, p. 30.)

CAMBRIAN AND ORDOVICIAN DOLOMITE.

The Cambrian and Ordovician dolomite in Ohio is dense and not very soluble and probably permits little if any water to penetrate it from its outcrop. Where opportunities occur, however, water doubtless penetrates it from the overlying saturated St. Peter sandstone or from other sandstones which may be below it. Water, if it occurs, will probably be found in solution passages representing enlarged joints or bedding planes. Although the Moerlein well penetrated it for 1,000 feet the dolomite gave no material addition to the supplies obtained from the St. Peter sandstone, and there is no reason to think that it will yield any usable supplies in southwestern Ohio.

SUMMARY OF AVAILABLE WATER.

Southwestern Ohio is particularly unfortunate as regards rock waters, good water-bearing formations being absent. The "Niagara" and "Clinton," as has been seen, yield moderate supplies to relatively shallow wells; the Richmond and Maysville supplies are uncertain; practically no water at all is obtained from the Eden shale, and only small amounts from the Point Pleasant formation; the "Birdseye" limestone and St. Peter sandstone yield saline or sulphur water, and the underlying beds within reach of the drill appear to carry no water whatever.

In the drift, however, especially in the northern half of the area, the region has a source of supply that is ample for all domestic and farm uses, and except along the Ohio, the alluvial gravels of the valleys afford abundant water for public supplies and for manufacturing purposes.

PUBLIC WATER SUPPLIES.

The public water supplies in southwestern Ohio are derived from streams, artificial ponds, springs, and wells. Stream water in its raw or unfiltered state is used only where, as at Cincinnati, the demand is too great to be supplied from any other source. Artificial ponds are seldom used as sources of supply in the Ohio Valley, as in most places more and better water can be obtained from wells. Springs furnish supplies for several towns and would doubtless be more generally utilized if they were more widely distributed, but they have origin mainly in a single geologic formation—the "Clin-

ton" limestone. Wells are by far the most important sources in the district, 90 per cent of the towns being so supplied. Most of them are in valleys and draw their supplies from the alluvium, but some are on the till uplands. The distribution of the public water supplies when the field work was done is indicated on Plate IV (p. 30).

The following table summarizes the principal public water supplies of southwestern Ohio in 1906, giving the ownership, source, number, diameter, depth, and head of wells, the system of distribution, services or taps, fire hydrants, daily consumption, domestic and fire pressure, and other data. Further particulars concerning many of the supplies are given in connection with the town notes, to which references are given in the table. Analyses of a considerable number of the waters will be found in the tables of analyses on pages 198 to 207.

Statistics of municipal water supplies in southwestern Ohio in 1906.

Town.	Population, 1910.	Ownership.	Source.	Geologic source.	Wells.			
					Number.	Diameter.	Depth.	Depth to water.
BROWN COUNTY.						*Inches.*	*Feet.*	*Feet.*
Georgetown	1,580	Public	Surface					
Ripley	1,840	do	Wells	Point Pleasant	4	4–6	108	
BUTLER COUNTY.								
Hamilton	35,279	Public	Wells	Alluvium	23	6–8	75–135	20
Middletown	13,152	do	do	do	1	[a] 25	36	16
					7	12	48	
Oxford	2,017	do	do	do	3		20–60	13
					1			
South Excello		Private	do	do	7	6	35	
CLARK COUNTY.								
Springfield	46,921	Public	Wells and filter galleries	Alluvium	1	[b] 30	22	20
CLERMONT COUNTY.								
Batavia	1,034	Public	Stream					
Loveland	1,421	Private	Wells	Alluvium	1	12	50	7
Milford	1,321	Public	do	do	3	6–8	64–72	24
New Richmond	1,733	do	Ohio River					
CLINTON COUNTY.								
Blanchester	1,813	Private	Surface					
New Vienna	793	Public	Wells	Niagara	4		60	±0
Wilmington	4,491	Private	do	Gravel under till	6	6–8	65–172	±0
DARKE COUNTY.								
Arcanum	1,361	Public	Wells	Niagara	6	8	38–80	
GREENE COUNTY.								
Osborn	866	Public	Wells	Alluvium	4	8		
Wilberforce		Private	Springs	Till				
Xenia	8,706	do	Wells and springs	Gravel under till	14	6–10	30–40	10
HAMILTON COUNTY.								
Arlington Heights	798	From Wyoming						
Bond Hill	1,081	From Cincinnati						
Carthage	3,618	Public	Wells	Alluvium	4	6	135	
Elmwood	3,423	From Carthage						
Glendale	1,741	Public	Wells	Alluvium	2	8		
Harrison	1,368	Private	do	do	4	3	100±	
Hartwell	1,823	From Wyoming						
Hyde Park	1,691	From Cincinnati						

[a] Feet.

Statistics of municipal water supplies in southwestern Ohio in 1906—Continued.

Town.	Population, 1910.	Ownership.	Source.	Geologic source.	Wells.			
					Number.	Diameter.	Depth.	Depth to water.
HAMILTON COUNTY—continued.						*Inches.*	*Feet.*	*Feet.*
Idlewild		From Norwood						
Kennedy Heights	598	From Cincinnati						
Lockland	3,439	From Wyoming						
Madisonville	5,193	Public	Wells	Glacial gravel	3	6–8	150	21
Norwood	16,185	do	do	do	2	10	260	
Pleasant Ridge	1,769	From Cincinnati						
Reading	3,985	Public	Wells	Glacial gravel	3	8	150	50
St. Bernard	5,002	do	do	Alluvium	2	14	270	40
Wyoming	1,893	do	do	do	4	8	164–197	45
HIGHLAND COUNTY.								
Hillsboro	4,296	Public	Wells	Alluvium	11			
Leesburg	828	do	do	Niagara (?)	4			
Lynchburg	923	do	Springs	Glacial drift at top of rock.				
MIAMI COUNTY.								
Tippecanoe	2,038	Public	Wells	Alluvium	3	6	55–65	12
West Milton	1,207	do	Springs	Top Clinton limestone				
MONTGOMERY COUNTY.								
Brookville	1,187	Public	Wells	Top Niagara	4	6–8	80	±0
Dayton	116,577	do	do	Alluvium	77		30–60	10
Miamisburg	4,271	do	do	do	5	8	60	
National Military Home		Government	do	Gravel under till	16	6	45–58	35
Oakwood	358							
Trotwood	348	Private	Wells	Alluvium	2	6	64	
West Carrollton	1,285	do	do	do		6–8	65	10
PREBLE COUNTY.								
Eaton	3,187	Public	Wells	Alluvium	2	6	50–100	±0
New Paris	870	Private	Well	Moraine	1		17	12
West Alexandria	1,030	Public	Wells	Alluvium	4	8	134	16
West Manchester	445	do	do	Till	3	9	64–67	
WARREN COUNTY.								
Franklin	2,659	Public	Wells	Alluvium	4	6–8	63	10
Lebanon	2,698	do	do	Glacial drift	4	6	96–104	±0
Waynesville	705	do	do	Alluvium	4		40	

Town.	Distribution or storage.	Taps.	Fire hydrants.	Average daily consumption.	Pressure.		Remarks.
					Domestic.	Fire.	
BROWN COUNTY.				*Gallons.*	*Pounds.*	*Pounds.*	
Georgetown							Not installed in July, 1906.
Ripley	Reservoir	240	90	100,000	140	140	
BUTLER COUNTY.							
Hamilton	Reservoir	4,300	265	2,500,000	96	96	More wells and larger pumps are planned.
Middletown	Direct	1,500	250	1,500,000	60	120	One 35-foot open well, others driven.
Oxford	do	350	53	135,000	45	45	Waterworks situated a mile from town and 175 feet lower.
South Excello	Reservoir	None.	7			80	Used for fire only.
CLARK COUNTY.							
Springfield	Standpipe	6,000	522	3,500,000	65	65	Eighty per cent from wells.
CLERMONT COUNTY.							
Loveland	Elevated tank	300	30				In process of installation, 1906.
Milford	Standpipe	160	40	55,000	85	85	
CLINTON COUNTY.							
New Vienna	Standpipe	125	35	10,000	60	100	
Wilmington	do	180	81	30,000	50	110	Raised by air lift.
DARKE COUNTY.							
Arcanum	Direct	225	35	25,000	58	75	
GREENE COUNTY.							
Osborn	Standpipe	160	32		125	125	
Wilberforce	Tank						Used in college buildings only.
Xenia	Standpipe	1,200	200	500,000	55	55	
HAMILTON COUNTY.							
Carthage	Direct	450	51		65	90	
Glendale	Standpipe	160	29	150,000	45	95	
Harrison	do			30,000	40	100	
Madisonville	Direct	350	85	125,000	50	85	
Norwood	Standpipe	2,100		750,000	100	100	
Reading	Reservoir	200	58	90,000	85	85	
St. Bernard	Standpipe		68		80	80	Well enters rock at 135 feet. Water at 128 feet.
Wyoming	Reservoir	800	125	480,000	110	110	Includes Arlington, Hartwell, and Lockland.

Statistics of municipal water supplies in southwestern Ohio in 1906—Continued.

Town.	Distribution or storage.	Taps.	Fire hydrants.	Average daily consumption.	Pressure.		Remarks.
					Domestic.	Fire.	
				Gallons.	*Pounds.*	*Pounds.*	
HIGHLAND COUNTY.							
Hillsboro	Standpipe	700	72	300,000	50	50	
Lynchburg	Elevated tank	150	24	20,000	50	140	Direct pressure during fires. Water possibly from base of Clinton limestone.
MIAMI COUNTY.							
Tippecanoe	Direct	500	55	115,000	40	80	
West Milton	Elevated tank	200	30	135,000	75	75	
MONTGOMERY COUNTY.							
Brookville	Air-pressure tanks	100	40	40,000			
Dayton	Direct	17,700	1,500	6,200,000	60	125	
Miamisburg	do	225	96	200,000	65	100	New system.
National Military Home	Reservoir						
Trotwood	Air-pressure tank	30			75		
West Carrollton	Direct	130			60		
PREBLE COUNTY.							
Eaton	Standpipe	570	76	120,000	58	150	
New Paris	Direct	20					
West Alexandria	Standpipe	170	14	50,000			
West Manchester	Compressed air				25–500	100	
WARREN COUNTY.							
Franklin	Direct	480	65	200,000	65	100	
Lebanon	Standpipe	670	78	125,000	70	120	
Waynesville	do	100		40,000	70	70	

USE OF REPORTS AND MAPS.

Determination of surface deposits.—Over the greater part of southwestern Ohio the unconsolidated surface deposits are more valuable as water-bearing beds than are the underlying rock formations and it is therefore important that their nature at any given point should be readily ascertainable. Their character at the larger cities and towns may be determined at a glance from Plate II, which shows the distribution of the glacial or surface deposits of the region. At smaller towns not shown on the map the nature of the surface materials can be determined from the table showing underground-water conditions given for each county (see county descriptions). Places away from a town or village may be approximately located on the map (Pl. II), and the surface formation readily determined.

Determination of country rock.—Like the unconsolidated or surface deposits, the country rock or bedrock immediately underlying any of the larger cities and towns can be determined directly from the geologic map (Pl. I), which shows the distribution of the rock formations beneath the surface deposits. Likewise, the rock formations beneath the smaller villages may be determined from the tables in the county description or from the map.

Best source of supply.—Although it is a common belief that good supplies can always be obtained by going "deep enough," this is not necessarily true. In some localities the deep supplies are the best; in others the shallower waters are preferable; and in still others no great difference exists between the two. To ascertain which is the best supply at a given town or village, the table of underground-water conditions in the county descriptions should be consulted. These will show the relative amounts of the supplies of the surface deposits and of the surface rocks and indicate the best of the rock sources and its probable supply. If the point at which the supply is desired is not in a town or village it should be located on the map of glacial or surface deposits (Pl. II) and on the geologic map (Pl. I), as already explained. The nature of the surface deposits and underlying rock being thus determined, the relative water-bearing capacities can be found by consulting the general table of rock formations (pp. 22–23) and the descriptions of surface deposits and rocks (pp. 23–30).

Thickness of surface deposits.—Many factors affecting the success of wells hinge on the thickness of the surface deposits. Some formations, like the till, which when thick are strong water bearers, are of little value when thin; hence the thickness of the deposit becomes a matter of great importance. Again, the cost of drilling and the length of casing required is materially affected by the relative amounts of surface and rock formations to be penetrated.

To determine the thickness of the surface deposits or the depth to rock, at a given city or village, reference should be made to the tables of underground-water conditions (see county descriptions), which give the exact depth where this has been disclosed by wells and the estimated depth where the actual depth is unknown. The thickness of the surface deposits outside the cities and villages may be found by locating the point on the map showing the thickness of the surface deposits (Pl. III).

Depth to water in the St. Peter sandstone.—For some uses, such, for instance, as cooling, volume of water is principally desired and quality is of minor importance. To obtain a supply for this use wells may be sunk to the St. Peter sandstone, whose water, though of little value if quality alone is considered, is cold and abundant. Too few wells have been sunk to the formation to permit accurate determination of its depth in this region. Fortunately, however, during the oil and gas boom 25 to 30 years ago many wells were sunk to the "Birdseye" limestone, and it has been possible, by means of contours on the artesian-water map (Pl. IV, p. 30), to fix the elevation with reference to sea level of that limestone throughout the area. To determine the depth to the "Birdseye" at any given point the elevation of the rock contour should be subtracted from the elevation indicated by the surface contour, the position of the rock contour above or below sea level as indicated by the plus or minus sign being considered. To find the depth to the water-bearing bed in the St. Peter add 700 feet (the approximate distance of the principal water bed of the St. Peter below the top of the "Birdseye") to the figure already obtained; the result will be the approximate total depth to the main supply in the St. Peter.

Flowing wells.—A few wells in the higher formations flow, but there is no general artesian bed in southwestern Ohio above the St. Peter sandstone which carries water that is under considerable head. Although this sandstone lies far below sea level, even at Cincinnati, its water will rise to 590 feet above the sea if penetrated by wells and will flow wherever the surface elevation is less than 590 feet, except where, as at Cincinnati, its head has been reduced by the drilling of numerous deep wells. To determine whether or not a flow may be expected it is, in general, simply necessary to find whether the well mouth is above or below the 590-foot level. This may be determined from the artesian-water map (Pl. IV, p. 30), on which the area below this level is indicated.

Water-bearing capacity of formations.—The character of each of the rock formations and their water supplies are concisely described in the generalized section of rock formations on pages 22–23 and are described in detail on pages 28–31.

Distribution of surface deposits and rock formations.—The general distribution of the rock formations is shown on the geologic map (Pl. I), and the distribution of the surface deposits is shown on Plate II. Further details of the distribution will be found in the county descriptions.

Quality of water in particular deposits and formations—The quality of the underground waters in southwestern Ohio is set forth in Table 2 (p. 208), in which the analyses are classified according to their occurrence in the several surface deposits and rock formations.

UNDERGROUND WATER BY COUNTIES.

ADAMS COUNTY (WESTERN HALF).

By M. L. Fuller.

In the field investigation for this report the work in Adams County was confined mainly to the western half, or to that part lying west of a north-south line drawn through a point about 2 miles east of West Union, and the following descriptions are limited to this area.

SURFACE FEATURES.

Adams County, like other counties similarly situated, is marked along Ohio River and its tributaries by a rather rough topography, crests standing 400 to 500 feet above the river, alternating with valleys or ravines of equal depth. Farther back from the river the streams have not cut so deeply, and the uplands are gently rolling or even flat. Even where the stream cutting is deepest the crests between the streams, although narrow, are generally flat. Along the Ohio the thin mantle of yellowish silt or loess somewhat softens the surface relief, and in the northwestern part of the county the drift, though very thin, helps to make the surface still flatter. The elevation of the uplands ranges between 950 and 1,000 feet.

WATER-BEARING FORMATIONS.

The water-bearing formations include the alluvium, the loess, and the pebbly clay or till, among the unconsolidated deposits, and the "Niagara" and "Clinton" limestones, the Richmond and Maysville formations, and the Eden shale among the harder rocks.

SURFACE DEPOSITS.

ALLUVIUM.

The most extensive alluvial deposits, those along the Ohio Valley, include not only the recently deposited materials of the present stream but also much gravelly outwash brought down by the glaciers

which formerly occupied the region to the north. Although of diverse origin, the materials differ little in character and are not readily separated even on the ground. The alluvial deposits consist of silts, sands, and gravels, the latter two predominating in general, but including clays of considerable thickness at some localities. The general arrangement seems to be as follows: (1) A surface layer of loamy sand or sandy clay over the flood plain, (2) 10 feet or more of clay with some very fine sand, and (3) alternating layers of sand, gravel, or clay to a depth of 50 to 100 feet or more.

Along the smaller streams the alluvium is thinner and even more varied in composition, ranging from fine silts in the flat, shallow valleys on the upland plateaus to coarse gravel in the ravines.

The water supplies of the silty alluvium are small and uncertain, and in many of the flat upland valleys this material is therefore not available as a source of water. The gravels of the ravines will almost always yield water where they are 10 feet or more in thickness, provided the valleys do not slope so steeply that little water is retained. In the more extensive deposits, such as those along the Ohio, although certain layers, like the clay beds, may be destitute of available water, there are nearly always beds of gravel or sand within moderate depths which will yield abundant supplies.

LOESS.

The loess is a yellowish, more or less clayey silt, forming a mantle over the rocks of the uplands near the Ohio River. It is usually very thin, though locally reaching several feet in thickness. In Adams County it may furnish small supplies of water to dug wells, but is generally too thin to be of importance except as a feeder to collect and supply waters to the underlying rocks.

TILL.

The yellowish or bluish, more or less pebbly, clay known as till is found only near the northwest corner of Adams County, and even here it has a thickness at the most of only a few feet. In the counties to the north it is an important water bearer, but in Adams County it is of value only as a feeder to the underlying rock. In conjunction with the disintegrated underlying rock it affords in some localities a source of supply to shallow dug wells.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

The "Niagara" limestone may be roughly divided into a limestone bed a few feet thick at the base, an overlying shaly bed about 100 feet thick, and an upper limestone about 90 feet thick. It forms

the upland levels between all the streams in the western part of Adams County, but is not found in the valleys, the streams having cut through it and the underlying "Clinton" into the Richmond formation.

Wells obtain more or less water throughout the thick upper limestone layer, but the principal source is at the bottom of this layer, along the contact with the underlying shale bed of the same formation. This contact, as elsewhere, is marked by a conspicuous line of springs. In places some water is afforded by the thin limestone at the base, but this bed is of less importance as a water bearer than either the shale contact above or the "Clinton"–Richmond contact below.

"CLINTON" LIMESTONE.

The "Clinton" limestone in Adams County is a semicrystalline pinkish or reddish limestone locally changing to an impure iron ore, especially along the Highland County boundary. It appears to have a thickness of 40 to 50 feet and is an upland formation, outcropping along the valleys just below the "Niagara" and at some of the lower spots on the general uplands.

The "Clinton" carries considerable water throughout its extent and is the source of many springs which emerge principally from the basal layers along the contact with the upper shaly beds of the underlying Richmond formation. Where not covered by the "Niagara," it commonly affords supplies to shallow wells, but where the "Niagara" is present most wells stop at the top of the 100-foot shale bed in that formation.

RICHMOND AND MAYSVILLE FORMATIONS.

Although 300 feet or more of the Richmond and Maysville formations is exposed in the county, most of the thickness is in the steep bluffs of the Ohio and its tributaries, only relatively small areas of the upland surface in the western and southwestern parts of the county being underlain by these formations. The top of the Richmond is marked by a 25-foot bed of blue and reddish shale, below which layers of limestone and shale alternate down to the river level. A zone in which shale commonly predominates occurs at the contact of the Richmond and the underlying Maysville, but in general the two formations show little difference in character and are best grouped together with respect to water supply. The line of separation would fall midway up the bluffs of the valley walls.

On the flat uplands in the western and southwestern parts of the county and to a certain extent on the more gentle valley slopes of some of the streams in the northern district shallow open wells obtain fair supplies of water from the Richmond. On the steeper slopes it may be necessary for wells to go down 40 or 50 feet to procure

adequate supplies. In the valleys the overlying alluvium affords better supplies than the rock. Drilled wells, although they may find some water, lack storage capacity and many fail to yield adequate supplies.

EDEN SHALE.

The Eden shale consists of bluish to grayish shales, with local thin layers of limestone. It underlies the Maysville formation and outcrops in the lower part of the Ohio bluffs at the extreme southwest corner of the county. The formation is about 250 feet thick, but only a small part of this thickness is exposed in Adams County. It contains practically no available water, and there is great difficulty in obtaining from it the supplies necessary for domestic use, even in dug wells. This absence of water is due in part to the compactness of the shale and the general absence of porous or soluble layers and in part to the poor catchment conditions, its outcrop on steep hillsides allowing the water to drain from it readily without absorption.

SPRINGS.

The Adams County Mineral Springs, also known as the Arcadia Springs, are in eastern Adams County and, although occurring outside the immediate area investigated, merit consideration because of their interest and importance. The springs issue in masonry basins at the base of high hills bordering a small valley, the water coming from a blue slaty shale which is believed to represent the Ohio shale (Devonian). The volume of each of the two principal springs is small but is constant throughout the year, supplying enough for all the guests at the resort. The temperature on September 13, 1906, was about 58° F. The water, as shown by the analysis (pp. 198–199), is high in sulphates and contains free sulphuric acid. Rusty-looking growths or deposits can be seen about the springs, which, with the hotel, are owned by S. R. Grimes.

NOTES BY TOWNS.

WEST UNION.[1]

The town of West Union is situated on a high plateau underlain by "Niagara" limestone. Most of its open wells enter the rock at 4 to 6 feet and penetrate it from 22 to 35 feet to procure their supplies. At 40 to 45 feet they enter the thick shale bed forming the lower part of the "Niagara," but obtain no water from it. They appear not to reach the "Clinton."

Wells sunk in the Richmond and Maysville formations in the valleys rarely obtain much water. A strong spring, yielding about

[1] Conditions in 1906.

10 gallons a minute, occurs on the pike one-fourth mile north of the courthouse, the water issuing from a vertical joint in the limestone. An analysis will be found in the table, pages 198–199.

WATER PROSPECTS.

The following table indicates the general underground-water conditions and water prospects at each of the more important localities in the western part of Adams County:

Underground-water conditions in Adams County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Bentonville	Loess and soil.	20		"Niagara"	"Clinton"	Usually plenty.
Cherry Fork	Till	20		do	do	Do.
Eckmansville	do	20		do	do	Do.
Emerald	do	10		do	do	Do.
Fairview	do	8	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
Harshasville	do	14		"Clinton"	"Clinton"	Usually plenty.
Manchester	Alluvium.	130+	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
Seaman	Till	20		"Niagara"	"Clinton"	Usually plenty.
Stephens	Alluvium.	Deep.		Eden	Point Pleasant.	Small.
Tranquility	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
West Union	Residual soil.	4	Moderate.	"Niagara"	"Clinton"	Usually plenty.
Wheat	do			do	do	Do.
Winchester	Till	20		do	do	Do.
Wrightsville	Alluvium.	64+	Plenty	Richmond and Maysville.	Eden	Small.

BROWN COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

Near the Ohio and its larger tributaries much of the surface of Brown County is decidedly rough, owing to the deep valleys and ravines cut by the streams. In the northern part, however, it is essentially a plateau 950 to 975 feet above sea level, but even there it is cut by a few deep valleys. Plateau remnants in the shape of flat-crested ridges appear between the streams in the southern half of the county, their average elevation being between 900 and 950 feet. The plateau surface in the north is rendered still more flat by a smooth sheet of till.

WATER-BEARING FORMATIONS.

The water-bearing formations of Brown County include among the surface deposits alluvium, terrace gravels, loess, and till, and among the rock formation the "Niagara," "Clinton," Richmond, and Maysville formations, and the Eden shale.

SURFACE DEPOSITS.

ALLUVIUM.

The principal deposits of alluvium in Brown County are along Ohio River, where they are commonly 100 to 150 feet thick and one-half mile to a mile or more wide. Smaller, but still fairly extensive deposits occur in the larger tributaries of the Ohio, and small accumulations are found in the ravines entering the streams mentioned.

The alluvial deposits of the Ohio consist of loamy sand or sandy clay at the surface, in many places grading downward into clay deposits more than 10 feet thick. Below the clay porous gravels or sands are commonly found in beds of considerable thickness, many of them alternating with clayey beds. The alluvium in the larger tributary valleys is similar, in a general way, to that in the Ohio Valley, but much of that deposited by the rapidly flowing streams in the ravines is very coarse and gravelly. Locally, thin tills may be included in the alluvium.

An abundant supply of water can usually be obtained from the gravel beds underlying the clays in the Ohio Valley and from the sandy and gravelly beds in the valleys of the tributaries and in certain of the ravines.

TERRACE GRAVELS.

Terraces of gravel, marking a stage of the Ohio when it flowed at a level higher than at present, occur at numerous points along the valley. Owing to their situation water entering them is quickly drained away to the river or into the underlying formations, and wells penetrating them must commonly go down nearly or quite to the river level to obtain supplies.

LOESS.

Along the crests of the bluffs facing the Ohio and for some distance inland the surface is covered by a few feet of the yellowish to white, somewhat clayey silt known as loess. Although capable of holding water this deposit is usually so thin that it is not a good source of supply. Wells pass through it into the underlying till or rock within a few feet of the surface.

TILL.

The yellowish or bluish pebbly clay or till covers the entire county except the southeast corner. The thickness varies from 10 to 20 feet in the northern part of the county to the vanishing point along the southern edge of the drift, which appears to extend a little north of east from Ohio River near Higginsport through Cedar Point, Red Oak, and Decatur.

Owing to the thinness of the drift it is much less important as a water-bearing formation in Brown County than in the counties to the north and west. It helps, however, to collect and hold the water and gradually feeds it to the underlying rocks. Together with the loess and the disintegrated rock due to surface weathering, it locally affords to shallow wells supplies that are very fair but that are much less likely to be permanent than where the drift is deeper.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

The "Niagara" limestone, which is so important as a water-bearing bed to the east, barely touches the eastern boundary of Brown County, in which it furnishes little or no water.

"CLINTON" LIMESTONE.

The "Clinton" limestone outcrops in the extreme eastern part of the county near the Adams County line, being found just west of the "Niagara" limestone outcrop. As elsewhere in southwestern Ohio a large number of springs emerge near its base and it supplies a few shallow wells, but its area in the county is so small that it is of little importance as a water-bearing bed.

RICHMOND AND MAYSVILLE FORMATIONS.

The Richmond and Maysville formations constitute the upland surface over almost the entire area of Brown County and form the upper part of the bluffs bordering the streams. In its upper few feet the Richmond is shaly, but not far below the top it exhibits the usual alternation of thin layers of limestone and shale. The Richmond is considerably thinner here than at many other points. The Maysville, into which it grades downward, is very similar in composition. Shale predominates near the contact.

The Richmond and Maysville formations contain considerable water, although, owing to the large amount of shale present, their water-bearing passages are neither large nor extensive. Shallow wells, especially where loess or drift coverings serve as feeders, yield

fair supplies, but few drilled wells procure water except in small quantities.

EDEN SHALE.

The Eden shale consists of bluish to grayish shales, weathering yellow or brownish and containing some thin limestones, but few or no sandy layers. The total thickness of the formation is about 250 feet, nearly all of which is exposed in Brown County. The bed outcrops almost entirely in the bluffs bordering the Ohio and its tributaries, none of it being found on the upland flats.

Owing to the absence of porous sandy layers and of persistent limestone beds there is little opportunity for the circulation of water, so that the formation almost never yields supplies of any consequence, except to shallow wells at the surface, where it has been broken up and loosened by the action of the weather. No drilled wells are known to procure water in this formation.

NOTES BY TOWNS.

GEORGETOWN.[1]

The location of Georgetown on the upland plateau, the thinness of the drift, and the absence of alluvium or of any good water-bearing rock formations have made it impracticable to obtain a public supply from wells. A dam has, however, been constructed to impound surface waters on a small basin, and in the summer of 1906 a pumping plant was about to be erected.

RIPLEY.[1]

Ripley, in 1906, drew its public supply from four wells, two penetrating 100 feet of gravel and two striking the limestones of the Point Pleasant formation 68 feet below low water of the Ohio and penetrating them for 40 feet. Additional data will be found in the table, page 51.

SARDINIA.[1]

Sardinia, situated on the plateau, has some exceptionally strong shallow wells, the public well opposite Stephan Bros.' store, although only 11 feet deep, has been known to water 1,000 head of stock in a day without lowering the supply. An analysis of the water, which is derived from gravel, is given on pages 198–199.

WATER PROSPECTS.

The water prospects and general underground-water conditions in the several towns and villages of Brown County are indicated in the following table:

[1] Conditions in 1906.

Underground water conditions in Brown County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Aberdeen	Alluvium			Eden	Point Pleasant.	Small.
Arnheim	Till	10	Plenty	Richmond and Maysville.	Richmond and Maysville.	Do.
Bardwell	do	25+	do	do	do	Do.
Bernard	do	15+	do	do	do	Do.
Biehn	do	35		do	do	Do.
Bondes Ferry	Alluvium			Eden	Point Pleasant.	Do.
Browntown	Till	45+	Plenty	Richmond and Maysville.	Richmond and Maysville.	Do.
Carlisle	do	15		do	do	Do.
Center Point	Alluvium	25		do	Richmond, Maysville, and Eden.	Do.
Centerville	Till	12	Fair	do	Richmond and Maysville.	Do.
Chasetown	do	12	do	do	do	Do.
Crosstown	do	15		do	do	Do.
Decatur	Till or	9	Moder	do	do	Do.
Desoto	Till	20		do	do	Do.
Eastwood	do	35		do	do	Do.
Ellsberry	Residual soil or loess.			do	do	Do.
Fayetteville	Till	20	Small	do	do	Do.
Feesburg	do	15		do	do	Do.
Ferristown	do	20		do	do	Do.
Fincastle	do	40		"Clinton"	"Clinton," Richmond, and Maysville.	Moderate.
Fivemile	do	20		Richmond and Maysville.	Richmond and Maysville.	Small.
Georgetown	do	15	Plenty	do	do	Do.
Greenbush	do	20		do	do	Do.
Hammersville	do	15		do	do	Do.
Hestoria	Alluvium			Eden	Point Pleasant.	Do.
Hiett	Residual soil and loess.			Richmond and Maysville.	Richmond and Maysville.	Do.
Higginsport	Alluvium	90+	Plenty	Eden	Point Pleasant.	Do.
Kirbysville	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Levanna	Alluvium	18	Plenty	Eden	Point Pleasant.	Do.
Locust Ridge	Till	18	Fair	Richmond and Maysville.	Richmond and Maysville.	Do.
Macon	do	14	Plenty	"Niagara"	"Clinton"	Usually plenty.
Maple	do	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Milltown	do	30		do	do	Do.
Mount Orab	do	50	Plenty	do	do	Do.
Neel	Residual soil or loess.			do	do	Do.
New Harmony	Till	30+	Plenty	do	do	Do.
New Hope	do	13	Fair	do	do	Do.
Prall	do	15	Small	do	do	Do.
Red Oak	Residual soil or loess.			do	do	Do.
Ripley	Alluvium			Eden	Point Pleasant.	Do.
Russellville	Till	20	Plenty	Richmond and Maysville.	Richmond and Maysville.	Do.

Underground water conditions in Brown County—Continued.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
St. Martins	Till	30+	Moderate.	Richmond and Maysville.	Richmond and Maysville.	Usually plenty.
Sardinia	...do	30	Plenty	...do	...do	Do.
Skiffsville	...do	15		...do	...do	Do.
Stickaway	Residual soil or loess.			...do	...do	Do.
Stringtown	Till	15		...do	...do	Do.
Sunshine	...do	12		...do	...do	Do.
Surryville	...do	30		...do	...do	Do.
Taylorsville	Residual soil or loess.			...do	...do	Do.
Union Plains	Till	25		...do	...do	Do.
Vera Cruz	...do	20		...do	...do	Do.
Wallsburg	...do	16	Fair	...do	...do	Do.
Whiteoak	...do	25+		...do	...do	Do.

BUTLER COUNTY.

By F. G. Clapp.

SURFACE FEATURES.

The upland surface of Butler County forms a plateau which has a maximum altitude of 850 to a little over 900 feet above sea level. Across the uplands the broad, flat surface and even sky line are very noticeable, but in the lowlands the plateau character of the county is not apparent, because the surface has been eroded and cut into by the streams. The larger valleys are broad and deep and generally extend several hundred feet below the surface of the uplands.

The principal stream, Miami River, flows southwestward across the county from the northeast corner, near Middletown, to Venice, at an elevation of 500 to 600 feet, about 300 feet below the level of the surrounding hills. Its valley ranges in width from 1 to 3 miles and consists of a broad flood plain and bordering terraces. Several broad valleys at elevations of 550 to 650 feet, carved by Miami River and its tributaries, are not now occupied by any large stream. The largest of these abandoned valleys extends southeastward from Hamilton and is traversed by the Pittsburgh, Cincinnati, Chicago & St. Louis Railway and the Cincinnati, Hamilton & Dayton Railway. In places there are enlargements of the main valley, which consist of local basin-like valleys 2 to 4 miles in diameter. The tributary valleys are of all sizes; in width they range from a few hundred feet to over a mile, and in depth they descend from a few feet below the plateau surface on the uplands to the level of Miami River. The slopes along the main valleys are generally steep and in places form pre-

cipitous bluffs, but back on the uplands they are moderate and grade into the gentle undulating surface.

WATER-BEARING FORMATIONS.

SURFACE DEPOSITS.

ALLUVIUM.

As would be expected from the unusual width of the main valleys, deposits of alluvium are extensive in Butler County. Along the side valleys they range in width from only a few hundred feet to a mile or more, but along the main Miami Valley they are 1 to 2 miles broad. On Indian Creek, Fourmile Creek, and Sevenmile Creek they range from a quarter of a mile to a mile in width. In most of the valleys the depth of the alluvial deposits is not known, for in their centers few wells are sunk to bedrock. Wells at Hamilton and Coke Otto are 50 to 100 feet deep and do not reach rock, the average depth of the alluvium in the center of the valley being probably nearly 200 feet. In the broad abandoned valley southeast of Hamilton the depth may be 50 or 100 feet more on account of the greater elevation of the deposits.

The deposits classed as alluvium consist of silt, sand, gravel, and a few layers of clay and hardpan (a thin deposit of pebbly clay or till). The alluvial deposits are generally finer and more silty in the upper few feet than in the deeper beds, because they consist of the finer silty materials deposited by overflows of recent streams flowing at a gentle grade.

In the alluvial deposits water lies a few feet below the surface, the exact depth depending on the proximity to and elevation above the streams, the configuration of the surface, and other conditions. The finer portions of the alluvium contain little water because of their generally impervious nature. In the greater part of it, however, water is abundant in sand and gravel at all depths from 30 feet downward, the coarse gravels containing the largest amounts. In a few localities, which can not be detected by inspection of the surface, the silty or clayey deposits continue to greater depths, making successful wells impossible.

TERRACE GRAVELS.

Accompanying the deposits of alluvium along the sides of the Miami Valley and extending up Indian, Fourmile, Sevenmile, and other large creeks are broad, low terraces, consisting of sand and gravel, which stand at elevations of 10 to 50 feet above the flood plain. In certain localities along these main valleys, but especially along the Miami, flat gravel terraces a few hundred or a few thousand

feet in extent stand 50 to 100 feet higher than the broader terraces. The gravels in some of these terraces are cemented and form a hard conglomerate, which in a few places along the sides of the valley breaks off in large bowlders. The water on the terraces is essentially the same as that on the flood plain, but it is not found so near the surface, for the terrace materials are more or less porous, and as they lie at higher elevations their water table is lower.

TILL.

The material known to geologists as till consists of a pebbly clay which for a few feet below the surface is yellowish but lower down is bluish gray, the change being due to the fact that near the surface it has been oxidized by the atmosphere. Till is found most abundantly on the uplands and occurs in the lowlands only beneath more superficial deposits of alluvium and terrace gravels. In the uplands of the southern part and in some in the northern part of Butler County the till is only a few feet thick. In general, however, it thickens toward the north. In considerable areas north of Hamilton it forms broad, rather flat plains from a few hundred feet to half a mile or more in extent which are similar in surface configuration to the gravel terraces but differ in not having their upper surfaces at a definite level and in being less even. Along Fourmile Creek good sections of these terraces show till ranging from 10 to 50 feet in thickness, and in many places on the uplands the till is believed to be equally thick. On account of the abundance of morainal deposits in the northern part of Butler County the till is obscured and its thickness can not be determined, but it is believed to fill many abandoned valleys and in such places it may have a thickness of over 100 feet.

The greater part of the till is very clayey and impervious, and for that reason contains relatively small amounts of water. It includes, however, local gravelly portions which hold some water, and even the clayey portions are saturated at a few feet below the surface. Dug wells in it obtain moderate supplies of water in a wet season, but after a long dry spell they are likely to give out, making it necessary, where practicable, to resort to deep rock wells. In dug wells in till the water generally stands 5 to 15 feet below the surface of the ground. Generally it is under only a slight head and rises very little when encountered. No flowing wells are known in the till in this county.

MORAINAL DEPOSITS.

Morainal deposits are not so extensive in Butler County as they are in counties farther north. However, moraines composed of low knolls and ridges standing only a few feet above the surrounding surface cross the county in a general northeast-southwest direction.

One belt, not conspicuous on the surface, runs northeastward from a point near Shandon, passing just west of Hamilton. A second belt, broader and less definite and of somewhat greater thickness, extends northeastward from the vicinity of Oxford toward Preble County. Between these moraine belts lie many irregularly distributed deposits of gravel, sand, and pebbly clay which can not be definitely classified but which come under this type of deposit. Most of these morainal deposits are not shown on the maps, as they are not conspicuous on the surface. Of the broader and more prominent morainal deposits that are shown, one, touching the northeastern edge of the county, consists of conspicuous, well-defined undulating ridges and knolls of gravel. A less noticeable moraine, which forms the outer limit of the latest or Wisconsin ice advance, touches the southern border of the county at several places.

Owing to their general thinness, the morainal deposits in Butler County are not particularly important for water supplies, yielding only small amounts, which are found in dug wells and which vary in amount according to the season. The only morainal water of importance is found in the large moraine that touches the northeastern edge of the county, in which the supply is plentiful. In most places on this moraine, however, it is necessary to go to a considerable depth to get water.

ROCK FORMATIONS.

"NIAGARA" AND "CLINTON" LIMESTONES.

Both the "Niagara" and "Clinton" limestones occur near the southern edge of Preble County, but neither of them is known positively to extend into Butler County. They may be present east and west of Somerville, but if so they occur in small patches and have no effect on the underground water supply.

RICHMOND AND MAYSVILLE FORMATIONS.

The whole thickness of the Richmond and Maysville formations is exposed in Butler County, although the complete section is not exposed at any one point. These formations constitute the surface of the hard rocks throughout the county except for a few feet of the Eden shale, which is exposed along the Miami Valley near Venice and Shandon and extends northward a short distance toward Hamilton. It is possible also that a few small patches on the uplands in the extreme northern part of the county may consist of the "Clinton" and perhaps the "Niagara" limestone, but this can not be affirmed with certainty.

In general the Richmond and Maysville formations dip northwest. They consist of gray to blue limestone layers a few inches thick, alter-

nating with prevailingly calcareous clay shales. The best sections can be seen in several quarries west of Miami River, between Hamilton and Coke Otto, where unfossiliferous blue shale alternates with crystalline and somewhat fossiliferous blue-gray limestone. The limestone beds are from half an inch to 6 inches thick, and the shale beds 1 inch to 6 inches thick.

Owing to the thinness of the limestone beds, to the scarcity of solution passages, to the absence of porous layers, and to the predominating shaly nature of the beds, the Richmond and Maysville formations are not strong water bearers. Where they are covered by a few feet of drift, as over the greater part of the uplands, the water held in the drift commonly penetrates downward into the upper part of the Richmond and yields moderate supplies to dug wells. Drilled wells in these formations are not very successful, as they are so small in diameter that they do not admit enough water.

EDEN SHALE.

The Eden shale consists of gray or bluish-gray shales which weather brownish and have a maximum thickness of about 250 feet. Only a few feet of the upper portion is exposed in Butler County, outcropping along the lower Miami Valley, near the Hamilton County line, southwest of Hamilton, and possibly also for a short distance below the old gravel-filled valley southeast of Hamilton. No water is found in the Eden shale.

NOTES BY TOWNS.

COKE OTTO.[1]

At Coke Otto the Hamilton Otto Coke Co. has three 6-inch driven wells about 65 feet deep in alluvium. The material was reported to be gravel. Water was obtained at a depth of about 19 feet and rises within about 12 feet of the surface. The maximum yield by pumping is reported as 500 gallons a minute. The water is used for cooling gas. The wells can be pumped continuously. The normal level of water, 12 feet below the surface, can be lowered by ordinary pumping to 20 feet from the surface. By hard pumping it will descend to 25 feet but can not be lowered farther. The water level in the well is higher when the river is higher. The water is reported to be suitable for drinking. (See analysis, pp. 198–199.) Other wells at Coke Otto which do not belong to this company are driven to a depth of 18 to 25 feet. The head of the water depends on the depth to which the well is sunk below the level of the ground water, which is 12 to 15 feet below the surface.

[1] Conditions in 1906.

DARRTOWN.[1]

About 1½ miles southwest of Darrtown, on the flood plain of Fourmile Creek, the J. W. Nichols gas well was sunk several years ago to a depth of 2,051 feet. No reliable record of the formations passed through can be obtained, but it is known that gas was encountered at 608 feet and is now used for lighting a farmhouse near by. Salt water was obtained at about 1,100 feet. Very briny water was found somewhat below 1,200 feet and at other lower depths. The water in the well now stands about 100 feet below the surface, and gas comes up through it. This well was drilled in the hope of obtaining enough gas to supply the village of Darrtown, but it has never been used for this purpose.

HAMILTON.[1]

Hamilton is one of the largest cities in the region covered by this report. It is situated on both sides of Miami River and lies mostly upon the flood plain and gravel terraces but extends as much as 100 feet up the hills. The city is the center of a number of important manufacturing and other industries, and for that reason needs a large water supply. It has a good system of public waterworks, built in 1883, which supplies the greater portion of the inhabitants and industries. On the outskirts, however, many driven wells are sunk a few feet in gravel, obtaining ground-water supplies only 5 to 10 feet below the surface. It is recommended that where driven wells are used they should be sunk to somewhat greater depths, as the water near the surface is likely to be rather poor.

The waterworks consist of a pumping station obtaining water from 23 driven wells ranging from 75 to 135 feet in depth, situated on the flood plain at the north end of the city. The surface formation at that place is reported to consist of 175 feet of clean gravel, below which is 5 feet of blue clay resting on bedrock. The wells pass through some irregular pockets of sand, which contain little water. Owing to the fact that the wells are of various depths practically all the water available in the area in which they are sunk can be obtained. The water is pumped to a 6,000,000-gallon reservoir on Wilsons Hill 2 miles southwest of the pumping station, and 230 feet above low water level in Miami River. The pumps have a capacity of 4,000,000 gallons. The water, though very hard, is believed to be of excellent quality as regards organic purity, but the amount is not sufficient and larger pumps, more wells, and a larger reservoir are contemplated.

The Champion Coated Paper Co., whose mills are situated on the west side of the river at Hamilton, has 24 driven wells 6 inches in

[1] Conditions in 1906.

diameter and 80 to 120 feet deep, in gravel, from which water is obtained by pumps having a reported capacity of about 6,000,000 gallons. Ten of the wells are spaced 30 feet apart in two parallel rows 20 feet apart, and 10 more are similarly situated in two rows at right angles to the first 10. The other four wells were driven later. The water from these wells is mixed with river water and is used for cooling acid in the manufacture of paper. This plant is situated about half a mile southwest of the city waterworks, and the pumping is said to have affected the supply of the city wells.

The Champion Coated Paper Co. also has another well, which was drilled for gas to a depth of 3,120 feet. It found little gas, but large amounts of salt water. As shown by the analysis (pp. 198–199), the proportion of total solids (salt and other minerals) far exceeds that found in any other well which has been analyzed in the region covered by this report. The complete record of this well is reported by the company, as follows:

Record of Champion Coated Paper Co.'s deep well, at Hamilton.

	Thickness.	Depth.
	Feet.	*Feet.*
Limestone and shale (little gas)	.....	510
Small flow of gas	.....	1,015
Salt water	.....	1,045
"Birdseye" limestone	539	1,055
Much salt water	.....	1,075
St. Peter sandstone (salt water at 2,900 feet)	2,065	3,120

The drilling of the well lasted from June 4, 1904, to January 31, 1905. There was considerable trouble in casing and reaming, owing to the fact that the drill stuck several times. At 3,120 feet the well was abandoned and the casing taken out because the tools became fast and an attempt to drill around them proved unsuccessful. The casing ranges from 4 to 8 inches in diameter. The very strong brine was obtained 2,900 feet below the surface. A sample of water, which had been kept by the company in sealed hogsheads, was furnished to the Survey and analyzed by R. B. Dole and M. G. Roberts.

The Black-Clawson Co., the Niles Tool Works Co., the Miami Woolen Mills, the Hamilton Machine Tool Co., the Sterling Paper Co., the Becket Paper Co., and the Cincinnati Northern Traction Co. have driven wells ranging in depth from 40 to 200 feet, all obtaining water in alluvium. The water is hard but otherwise seems to be excellent. Some of these Hamilton wells are reported to have been pumped so continuously that they have drawn water away from other wells in the vicinity.

OXFORD.[1]

The water for the public supply of Oxford is drawn from one dug well and three driven wells, situated on the flood plain of the creek, about a mile north of the town and 175 feet below the main street. The system has been in operation since 1896. In all, seven wells have been sunk at the pumping station. Well No. 1 was sunk to 109 feet; at 29 feet gravel was struck, then a blue shelly material was penetrated, and at 109 feet "blue rock" was reached; all below 29 feet was abandoned. This is the deepest well in the group. The water reaches within 13 feet of the surface when it is being pumped. The other wells were sunk 60, 49, 22, 24, 23, and 22 feet.

In 1887 a well was sunk by the Oxford Gas & Oil Co. on the low flat opposite the railroad station. The following record[2] is based on samples of drillings preserved at the time:

Record of gas well, Oxford.

	Thickness.	Depth.
	Feet.	*Feet.*
Drift: Sand and gravel	40	40
Richmond and Maysville formations:		
Limestone	190	230
Limestone and shale	18	248
Limestone	17	265
Limestone and shale	115	380
Eden shale and part of Point Pleasant formation: Blue shale	407	787
Point Pleasant formation:		
Soft dark limestone and shale	3	790
Hard dark limestone	40	830
"Birdseye" limestone:		
White to gray crystalline magnesian limestone, with a little shale	450	1,285
Coarse dark-bluish or greenish limestone	45	1,330
St. Peter sandstone: White to bluish calcareous sandstone or arenaceous limestone (salty water)	40	1,370

This well starts 465 feet above low water in Ohio River.

SEVENMILE.[1]

The village of Sevenmile, situated on a low terrace near the flood plain of Sevenmile Creek, is supplied by private dug and driven wells ranging from 40 to 60 feet in depth. The water is obtained from gravel underneath hardpan. It is of very good quality except in a few shallow dug wells, but its level is not within 25 feet of the surface. The dug wells are reported to stop on top of hardpan and to obtain softer water than the driven wells which penetrate hardpan. They are, however, likely to dry up during the summer, whereas the driven wells never give out. A 48-foot well in Sevenmile passed through 40 feet of gravel, 8 feet of stony hardpan, and then into gravel. Just south of the village a test hole was once sunk to a depth of 1,485 feet in a search for oil. No details are available.

[1] Conditions in 1906.

[2] Abbreviated from record of J. F. James, Jour. Cincinnati Soc. Nat. Hist., vol. 10, 1888, pp. 73–77. Based on assumption that samples were taken at change of rock.

TALLEWANDA SPRINGS.[1]

A short distance north of College Corner, on the edge of Preble County, are situated the Tallewanda Springs, owned by the Joseph R. Peebles Sons Co., of Cincinnati. Two springs are in use, both being situated near the base of the ravine along a small run. No rock is exposed at this place and none is known by the owners, but the springs may issue from the "Clinton" limestone underlying the surface till. An analysis of the water is given on pages 198–199. The immediate surroundings of the springs are slightly wooded and there are cultivated fields some distance back from the run. The buildings are not so situated as to affect the quality of the water. The temperature of the water, as reported by the owners, is 48° F. It issues from the springs with measured volumes of 5 gallons and $5\frac{3}{4}$ gallons a minute. A little more water is reported in winter than in the summer, but the spring is not seriously affected by dry weather. The water issues in small gullies 40 feet above the run and is piped downhill to spring houses near the base of the slope, where it is bottled. It is shipped to Cincinnati and some of it is carbonated. The "still water" retails at 10 cents a gallon. It is claimed to be of great medicinal value. There is a bottling house on the grounds in which the water stands 5 feet in depth in a cement-lined tank. In addition to the two springs described, there is a third spring which forms a fountain. The Tallewanda Springs are named after the Tallewanda tribe of Indians who are said to have once encamped at them.

WATER PROSPECTS.

The prospects for obtaining water in the principal villages and towns in Butler County are summarized in the following table, which shows the nature of the surface materials and rocks and the character of the water supplies at each locality:

Underground water conditions in Butler County.

Town.	Surface deposits.			Rock formation.		
	Material.	Average thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Coke Otto	Alluvium	Deep.	Plenty.	Richmond and Maysville.	Richmond and Maysville.	Small.
College Corner	Morainal	30	do	do	do	Do.
Collinsville	Alluvium	Deep.	do	do	do	Do.
Darrtown	do	do	do	do	do	Do.
Hamilton	do	200	do	do	do	Do.
Lindenwold	do	Deep.	do	do	do	Do.
Millville	do	do	do	do	do	Do.
Oxford	Till	10	Small	do	do	Do.
Reiley	Alluvium		Plenty.	do	do	Do.
Sevenmile	do	50	do	do	do	Do.
Shandon (New London)	do	Deep.	do	Eden	None	
Somerville	do	do	do	Richmond and Maysville.	Richmond and Maysville.	Do.
Symmes Corners	do	do	do	do	do	Do.
Venice (Ross P.O.)	do	do	do	Eden	None	

[1] Conditions in 1906.

CLARK COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

The surface of Clark County is, in the main, a flat or gently rolling plateau, broken by the valleys of Mad and Little Miami rivers and their tributaries, which have been cut from 40 to 150 feet or more below the upland level. The valleys vary in width from a few hundred yards to about 2 miles, and the upland areas between the main streams are generally from 2 to 5 miles wide. Besides the irregularities due to stream cutting, there are many irregular hills representing morainal deposits left by the glaciers on their retreat from the region. Most of these hills are of no great height, but a few rise nearly or quite 100 feet above the surrounding territory. Though not forming connected ridges they fall into several general belts running from northeast to southwest, one lying along the eastern limits of the county, one east of and nearly parallel to Little Miami River, one west of the same stream, and one along the southeast side of Mad River.

WATER-BEARING FORMATIONS.

SURFACE DEPOSITS.

ALLUVIUM.

Alluvium is strictly a stream-laid deposit. Its upper part, in most places, is the work of the present streams, but its lower part may have been deposited by older streams which flowed before or between the several glacial advances in the region. The larger part of the alluvium is naturally found in the present surface valleys, but gravels deposited by old streams are present in many buried valleys beneath the pebbly clay. Probably the most notable of these buried valleys is the old channel of Mad River, near Sugar Grove, west of Springfield. North of this point the river flows on a filling probably over 100 feet in thickness, but to the south, at Limestone City, it flows not far above bedrock in a rock-walled valley only a few hundred feet wide. As the rock channel should normally be deeper, not shallower, at the downstream point, the conditions indicate that the river is out of its old channel. Railroad tests near Sugar Grove disclosed a deep rock channel beneath the surface deposits, cutting across the neck at this point and evidently marking an old channel of the river.[1] Another old channel, possibly marking a former course of the Miami, enters Clark County from the northwest near New Carlisle and joins the present Mad River Valley a few miles to the south. Other smaller buried channels have

[1] Orton, Edward, Geol. Survey Ohio, vol. 1, 1873, pp. 460–461.

been exposed in quarry excavations near Springfield, and it is probable that buried valleys abound throughout the county, although, owing to the fewness and shallowness of the wells, they can not be satisfactorily traced.

The valley deposits are not all alluvium, however, for between the deposition of the lower and upper portions ice advanced over the region, leaving sheets of pebbly clay over the old alluvium to be covered by later alluvium.

The alluvium or valley deposits, although embracing much fine silt, include large amounts of sand and gravel, which are usually saturated with water. Wells generally obtain water at or slightly above the level of the rivers flowing in the valleys, but as this water is generally so near the surface as to be liable to pollution, it is best to sink wells 20 or 30 feet below stream level. Few wells located near the center of the valleys fail to get adequate supplies, but the deposits near the borders are likely to be finer and to yield less water. The water is not usually under much pressure and rarely if ever flows at the surface.

TILL.

The pebbly clay or till which makes up the greater part of the surface deposits represents materials laid down beneath the ice sheets which once passed over the region and forms a mantle completely hiding the underlying rock. Although the surface of the till is generally flat and featureless, its thickness varies greatly owing to the irregularities of the rock surface on which it rests. In character it is mostly a sandy or pebbly clay containing sporadic bowlders, but it generally includes either definite beds of sand or gravel or zones that are predominantly gravelly. Near the surface it is usually yellow or brown from weathering, but at depths of more than 8 or 10 feet it is generally gray or bluish. The general thickness of the deposits is indicated on Plate III (p. 26) and local details are given in the town descriptions.

Although prevailingly clayey, the pebbly clay contains more or less gravelly layers or even beds of sand or gravel, in which water is usually present in abundance, standing in wet years within a few feet of the surface. In the flatter areas wells 25 or 30 feet in depth usually get sufficient supplies for ordinary use, and wells of 40 feet seldom if ever go dry. Near the borders of the deeper valleys, however, the supplies often drain away and wells have to be sunk considerably deeper. The water is sometimes under pressure, rising considerably when encountered, and flowing water may be obtained by wells here and there in the deeper ravines and along the base of the valley bluffs.

MORAINAL DEPOSITS.

Although the morainal ridges consist largely of sand and gravel deposited by waters that emerged from the ice margin during the glacial retreat, they contain a greater or less admixture of the unstratified pebbly clay or till. Generally, however, they are so open and porous that the water, instead of being retained, is drained away either to emerge as springs at their borders or to sink into the underlying pebbly clay. For this reason wells in the moraine areas must usually be carried to considerable depths, generally into the till, in order to procure adequate supplies, the morainal deposits themselves containing little or no available water.

ROCK FORMATIONS.

The rock formations known to underlie Clark County are the Richmond, "Clinton," and "Niagara." Later rocks may overlie the "Niagara" in the northeast corner, but because of the great thickness of the drift and the absence of borings their presence has not been established.

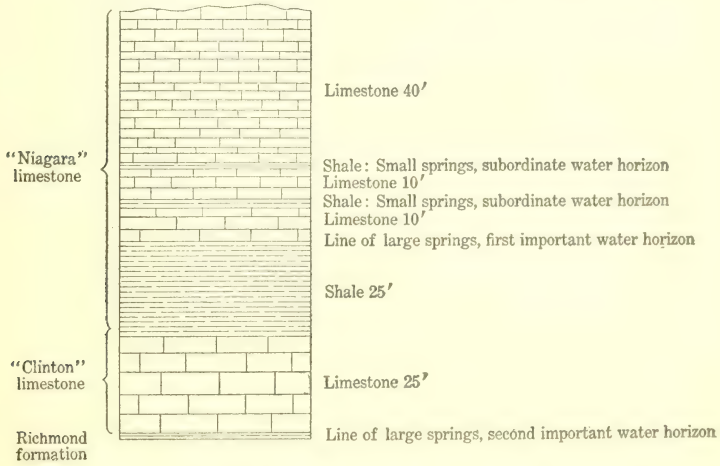


FIGURE 9.—Rock water-bearing beds of Clark County.

"NIAGARA" LIMESTONE.

The "Niagara" limestone, which is probably at least 100 feet in thickness, varies considerably in character in its different portions. Near the base of the formation, along the contact with the "Clinton" limestone, is about 25 feet of shaly limestone or calcareous shale, overlain in succession by about 8 feet of massive limestone, a thin parting of shale, about 15 feet of bedded limestone, known as the Springfield limestone, and about 40 feet of massive or irregularly bedded limestone unfit for building purposes. The "Niagara" limestone forms the surface of the entire county, outside the limits of the Richmond and "Clinton" formations, with the possible exception

of a small area of more recent rock in the northeast corner. Of the subdivisions of the limestone the uppermost, or 40-foot bed, is the most important, underlying by far the greater part of the county.

The lower shaly portion of the formation carries little or no water, but the limestone layers abound in solution passages and joints (Pls. V, *A;* VI, *A*), in many of which water occurs in abundance. The shales are of importance chiefly because they limit the downward penetration of the water, which collects it in the lower part of the overlying limestone beds, where it is available to wells or emerges as springs. In fact, the top of the lower shale layer is an important water horizon, giving rise to numerous springs, especially on the south side of the valley of Mad River, toward which the rocks dip. On the north side, where the dip is away from the valley, the springs are fewer in number and smaller in size.[1] It is to this horizon that the best rock wells throughout the country are sunk. Eight or ten feet above the lower shale and also about 20 feet above it occur thin shale partings, which to some extent act as barriers to the underground waters, but, although some wells get supplies from the beds above these layers, the amount is usually small and uncertain. To insure permanency the wells should be carried to the lower shale.

"CLINTON" LIMESTONE.

In Clark County the "Clinton" limestone is an irregularly bedded semicrystalline yellowish, pinkish, or reddish limestone about 25 feet thick. Its outcrop enters the county from the west a few miles north of New Carlisle and follows the east side of the valley of Honey Creek (West Fork), bending southeastward and reaching the Mad River valley south of Donnelsville and following it eastward to Snyderville. Here the outcrop crosses the river and runs southward east of Enon to the valley of Mud Run, the south side of which it follows to the county line east of the southwest corner.

The "Clinton" limestone is somewhat sandy and porous in its lower portion and in places carries a considerable quantity of water, which is retained by the underlying shales and emerges as strong springs all along the line of outcrop. Much of the upper part of the "Clinton" is in itself dense and impervious and also gives rise to springs at many points. The formation may be expected to yield satisfactory supplies to wells for a distance of several miles back from its outcrop and will probably afford small or moderate supplies over nearly the entire county.

RICHMOND FORMATION.

The Richmond formation, which consists of thin alternating beds of limestone and shales, underlies the alluvial deposits of the Mad River valley up to the vicinity of Snyderville, those of Mud Run

[1] Orton, Edward, Geol. Survey Ohio, vol. 1, 1873, p. 466.

south of Enon, and those of the West Fork of Honey Creek north of New Carlisle; but in few places does it outcrop above the valley deposits.

This formation doubtless contains considerable water, but as it is overlain either by the "Clinton" and "Niagara" limestones, both of which are better water bearers, or by the saturated alluvial deposits of the valleys, there is little occasion to sink wells into it, and it need not be further considered as a source of supply. Its upper portion is shaly and serves as an impervious layer to prevent the downward passage of the waters of the "Clinton."

NOTES BY TOWNS.

NEW CARLISLE.[1]

A deep well bored at New Carlisle in 1887, in search of oil and gas, struck the white "Birdseye" limestone at 1,060 feet, or about 150 feet below sea level. No oil or gas was found and the amount and character of the water were not reported.

NORTHAMPTON.[1]

A deep boring, known as the Mower well, sunk in 1887 near Northampton, penetrated 93 feet of drift and 1,287 of rock, or 1,380 feet in all. The "Birdseye" limestone was found at 1,293 feet. No oil or gas was found and no record of the water conditions is available. Most of the water appears to have been found in the upper part of the rock, as the casing was set at 200 feet.[2]

SPRINGFIELD.[1]

Several deep wells have been drilled at Springfield in search of oil and gas. One of these, sunk by J. W. Churchill for a local company in 1885, affords a good record of the underlying water-bearing beds.

Record of deep well at Springfield sunk by J. W. Churchill, 1885.[a]

	Thickness.	Depth.
"Niagara" limestone (58 feet):	*Feet.*	*Feet.*
Blue limestone	15	.....
White clay	3	.....
Shale	40	58
"Clinton" limestone (42 feet): White limestone	42	100
Richmond-and Maysville formations (710 feet):		
Red slate	12	.....
Shale [and limestone]	226	.....
Shell and gritty shale	37	.....
Gray shale [and limestone]	395	.....
Light shale [and limestone]	130	810
Eden and Utica shales (230 feet): Dark shale	230	1,040
Point Pleasant formation (100 feet):		
Red sand [and shale]	76	.....
Black shale	24	1,140
"Birdseye" limestone (top 190 feet below sea level).		

[a] Orton, Edward, Geol. Survey Ohio, vol. 6, 1888, p. 280.

[1] Conditions in 1906.

[2] Adapted from Orton, Edward, The Trenton limestone as a source of oil and gas in Ohio: Report. Geol. Survey Ohio, vol. 6, 1888, p. 278. The geologic formations are chiefly the interpretations of the authors of this report.

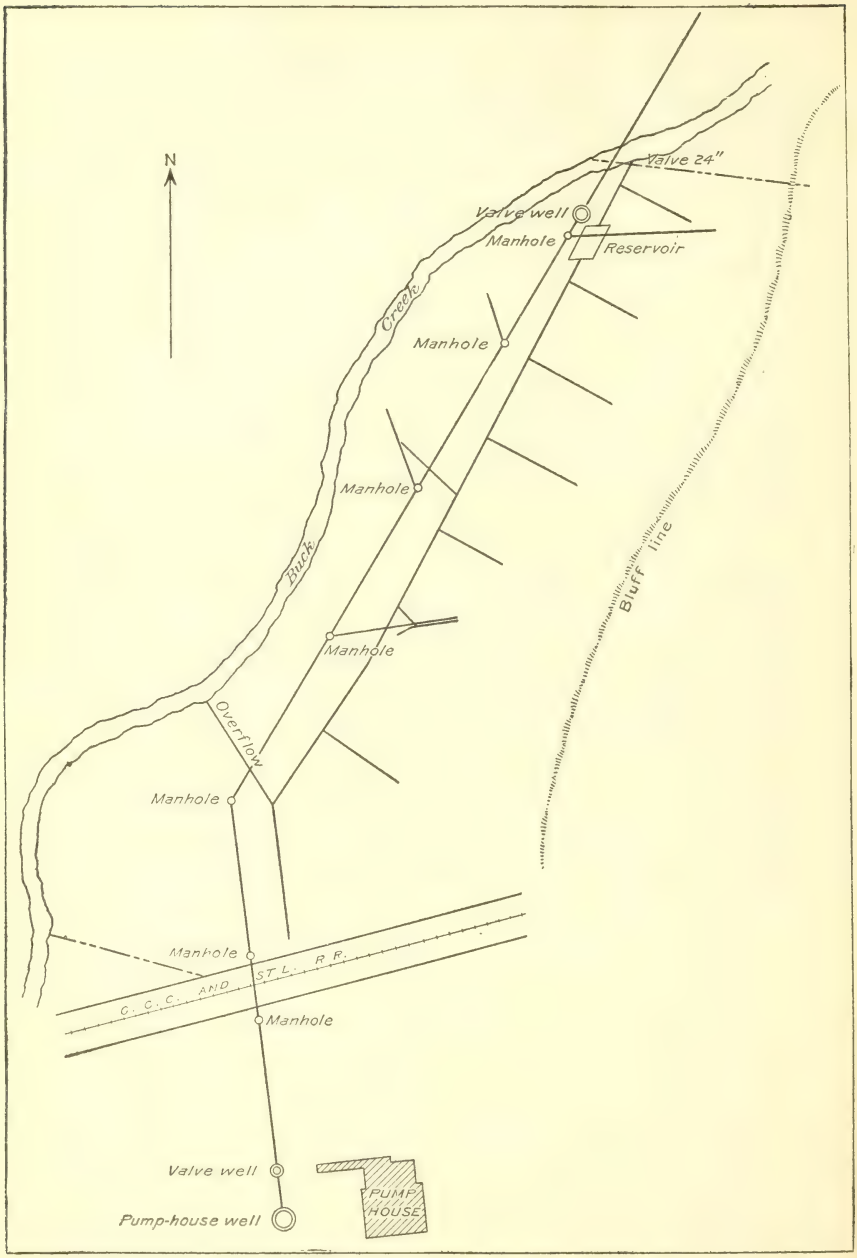


FIGURE 10.—Plan of infiltration galleries, public waterworks, Springfield.

About a year later, in 1886, a well drilled by the Champion Machine Co. to a depth of 2,400 feet or more developed the following strata:

Formations in Champion Machine Co.'s well, Springfield.

	Feet.
"Birdseye" limestone	1,200–1,900
St. Peter sandstone	1,900–2,000
Cambro-Ordovician dolomite (light colored)	2,000–2,400

Most of the fresh water appears to have been found in the first 250 feet, as the first casing was carried to this depth. Many salt-water supplies were encountered between 1,800 and 2,000 feet, probably mainly from the lower "Birdseye" and the St. Peter.

A public supply was first installed in Springfield in 1881, the water being obtained from a filter gallery, but on the speedy failure of this source, a reservoir 350 feet long, 200 feet wide, and 18 feet deep, with a capacity of 8,000,000 gallons, was built just above the junction of Beaver and Buck creeks, and a dam was built 300 feet below the junction of the creek to back up the ground water beneath the reservoir. In 1894 the combined supply of the original filter gallery and the reservoir, which was fed by seepage, having proved insufficient, an additional gallery 200 feet long, 32 inches wide, and 48 inches high was constructed, with laterals 20 feet below the surface in a gravel bed under and between the two creeks at their junction (figs. 10 and 11). This leads to a covered pump well 30 feet in diameter and 21 feet deep. Connection with the old gallery is also maintained (1906) and provision made for using creek water in case of severe fires. Statistical data regarding the waterworks will be found in the table on page 51 and an analysis of the water on pages 198–199.

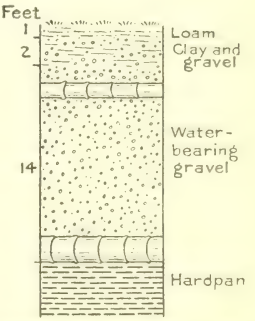


FIGURE 11.—Section of deposits at infiltration galleries, public waterworks, Springfield.

Several strong springs issue near the east end of the city park and are utilized for filling the large and picturesque artificial lagoons at this point. The water emerges from the base of the limestone cliff, in one place at a rate of 80 gallons and in another of 100 gallons a minute. No seasonal fluctuations have been observed. The water has a summer temperature of 52° and is rather hard. It is free from local pollution. Some difficulty has been experienced through the growth of algæ in the water, but this is now prevented by the use of copper sulphate, or blue vitriol, at intervals of about once a month. An analysis of this water is given on pages 198–199.

WATER PROSPECTS.

The following summary shows the character, thickness, and available water of the surface deposits and the underlying rocks in Clark County:

Underground water conditions in Clark County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rocks nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Beatty	Moraine on till	12	Plenty	"Niagara"	"Niagara"	Moderate.
Catawba	Till, moraine	50+		"Helderberg."	None as good as the till.	
Clifton	do	1–30	Moderate.	"Niagara"	"Clinton"	Do.
Cold Springs	Till	10	Small	do	"Niagara"	Do.
Donnelsville	do	12	Plenty	do	"Clinton"	Plenty.
Eagle City	Alluvium	Deep.	do	do	None as good as the alluvium.	
Enon	do	Deep.	do	Richmond	do	
Forgy	Till, moraine			do	Richmond	Small.
Hennessey	Till	15	Small	"Niagara"	"Niagara"	Moderate.
Hustead	do	15	do	do	do	Do.
Lagonda	do	80+	Plenty	do	do	Do.
Lawrenceville	do	100	Moderate.	do	do	Do.
Limestone City	do	0–5	Small	do	do	Do.
Midway	Alluvium	Deep.	Plenty	Richmond	None as good as the alluvium.	
New Carlisle	do	Deep.	do	do	do	
Northhampton	Till	90	Moderate.	"Niagara"	"Niagara"	Do.
Pitchin	Moraine, till	60+	do	do	do	Do.
Plattsburg	do	25+	do	do	do	Do.
Selma	Till, alluvium		Plenty	do	do	Do.
Snyderville	Till	10		"Clinton"	Richmond	Small.
South Charleston	Till, moraine	+50	Plenty	"Niagara"	"Niagara"	Moderate.
Springfield	Till, alluvium	20+	Moderate.	do	"Niagara" and "Clinton."	Do.
Spring Grove Park.	Till, moraine	35+	Plenty	do	"Niagara"	Do.
Vienna Cross-roads.	do	60+	do	do	do	Do.
Villa	do	50	do	do	do	Do.

CLERMONT COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

Clermont County, like the other counties of southwestern Ohio, lies on a table-land or plateau, the remarkably level surface of which stands about 500 feet above the Ohio, or about 900 feet above sea level. It is bordered on the south by the deep valley of the Ohio, but its interior is less cut by stream valleys than that of Hamilton County, to the west. Its deepest cut is that made by East Fork of Little Miami, which is the main drainage line of the county. Few tributaries of any consequence flow directly to the Ohio, although many short streams, occupying deep ravines, enter it. The bluffs facing the Little Miami and the East Fork are less steep than those of the Ohio and are only about 200 feet high. A few terraces border the larger streams.

WATER-BEARING FORMATIONS.

The water-bearing beds of the surface deposits include alluvium, terrace gravels, loess, and till; those of the harder rocks include the Richmond, Maysville, Eden, and Point Pleasant formations.

SURFACE DEPOSITS.

ALLUVIUM.

The most extensive alluvial deposits are those bordering the Ohio and occupying the valley of the East Fork of the Little Miami. As indicated above, most of the tributaries entering the Ohio are very small and the streams flow on bare rocks at many places. On some of the larger tributaries, however, small deposits of alluvium occur. The alluvium of the Ohio is generally a silty loam near the surface, merging downward into more or less clayey beds or tills, which in turn are underlain by sands and gravels. In the Little Miami Valley less silt is found, gravel and sand being more abundant.

Abundant water can be obtained from the sand and gravel beds below the clays of the Ohio flood plain, and similar supplies are yielded by the alluvium of the East Fork of the Little Miami. Water is also generally contained in the gravelly alluvium of the smaller valleys, provided the slope of the stream and of its deposits is not too great. In general the alluvium furnishes the most abundant and best supplies.

TERRACE GRAVELS.

Small patches of terrace gravels occur at points along the Ohio and the Little Miami, as, for instance, at Milford. The terraces are generally composed in the main of gravel and sand, but locally certain layers have been cemented by iron oxide into the hard sandstone or conglomerate, known to the inhabitants as cement rock. (See Pl. VI, *B*, p. 44.)

Owing to the gravelly nature of the terraces, water generally rapidly drains away or sinks into the underlying deposits, but in some places its downward passage is arrested by the cemented layers, which hold it in depressions and irregularities in their surface. (See fig. 8, p. 41.) It is not uncommon for wells to obtain water from the top of such beds, but if they do not find it they must generally continue to the level of the adjacent streams.

LOESS.

The entire surface of Clermont County, outside of the alluvial areas, is covered by a thin deposit of fine, more or less yellowish silt, which merges locally into whitish clayey deposit. The whitish clay,

however, commonly grades downward into yellowish or bluish clay of the same composition. The loess is most abundant near the Ohio, where its thickness may reach 5 or 10 feet. North of the East Fork of the Little Miami, however, it is much thinner, ranging from a few inches to a few feet. In a few places near the edge of the bluffs, where it is thickest, it affords supplies to very shallow wells, but farther back from the river it is too thin and serves principally as a feeder to the underlying till.

TILL.

The till of Clermont County belongs entirely to the older drift and has weathered yellowish to a depth of 10 feet or more, below which it is compact blue clay. It contains many pebbles and a few bowlders. In some localities peaty deposits or deposits of bog-iron ore have been found between the blue and yellow till. Springs occur at this level at many points.

ROCK FORMATIONS.

RICHMOND AND MAYSVILLE FORMATIONS.

The Richmond and Maysville formations consist of alternating layers of limestone and shale, rarely over 10 inches thick, but aggregating over 700 feet in all, of which about 600 feet is exposed in Clermont County. The two limestones together form the surface throughout the uplands of the county, the Richmond outcropping mainly in the northern half of the county and the Maysville in the southern half.

The Richmond and Maysville formations have no porous layers or thick seams of soluble limestone, and although affording moderate supplies of water to open wells, yield but little to wells of the drilled type.

EDEN SHALE.

The Eden shale is gray and blue in color, weathering yellowish or olive green. It has a thickness of about 250 feet, extending from a little below the flood plain to a point midway up the bluffs of the Ohio. Its outcrop extends up the Little Miami almost to the northern edge of the county and up the East Fork nearly to the western edge.

The Eden shale, owing to its outcrop on steep bluffs where the conditions of catchment are unfavorable and also to its clayey and impervious character, is almost destitute of ground water except in its weathered upper portion. In general, wells can not expect to obtain supplies from it. Fortunately, however, because of the location of its outcrop on slopes where inhabitants are few, wells in this formation are seldom needed.

UTICA SHALE.

A few feet of Utica shale occurs at the base of the Eden, but as a water bearer this formation is to all intents and purposes similar to the Eden and can not be looked to as a source of supply.

POINT PLEASANT FORMATION.

The Point Pleasant formation extends from low water up to a level just below the flood plain of the Ohio, its total thickness being about 50 feet. It consists of alternating layers of gray-bluish limestone and hard, dark-gray, compact sandy shale. Some of the limestone layers are of considerable thickness and are quarried for building stone.

Owing to its position beneath the flood plain of the Ohio and to the fact that better supplies can usually be obtained from the alluvium, few wells penetrate the Point Pleasant. Those that do, commonly find water in small amounts, which is likely to be brackish or to carry considerable sulphur.

LOWER FORMATIONS.

Below the Point Pleasant beds exposed at the surface, and entirely below the level of the river, there is 600 feet of massive grayish "Birdseye" limestone and 400 feet of porous St. Peter sandstone. Water is usually found in both of these formations, but is generally salty in the "Birdseye" and highly charged with both salt and sulphur in the St. Peter.

NOTES BY TOWNS.

BATAVIA.[1]

The public supply of Batavia was intalled in 1900, water being obtained from East Branch of Little Miami River at a point above the village. The water is first treated with alum in sedimentation tanks, from which it is carried by gravity through filter tanks provided with metal screens to a receiving or "clear-water" well, whence it is pumped to a cement-lined reservoir and distributed by gravity. The water (see analysis, p. 214) is reasonably safe after treatment and is to be preferred to that of the shallow wells, many of which are badly polluted.[2]

FELICITY.[1]

During the oil boom in 1887 a deep boring, said to have reached a depth of 1,200 to 1,400 feet, was sunk at Felicity. Salt-sulphur

[1] Conditions in 1906.

[2] For further details see Water-Supply Paper U. S. Geol. Survey No. 91, 1904, pp. 63–65.

water was obtained near the bottom, but no other supply of consequence was found.

LOVELAND.[1]

In 1906 a new public supply was being installed at Loveland by the Loveland Citizens' Electric Co., the water being obtained from a well 50 feet in depth sunk in the gravelly alluvium of Little Miami River a little above the town. The water (see pp. 200–201) is of good quality. It is decidedly safer than the water of the shallow wells in the crowded parts of town and should be entirely safe if care is taken to guard against local pollution. (See also p. 51.)

MARATHON.[1]

The spring of T. D. Hartman, at Marathon, which has some local reputation as a medicinal spring, issues with a volume of 5 or 6 gallons a minute from the drift in a small gully just below the upland level. The water is chalybeate and deposits some iron oxide along the small stream in which it flows. The statement that the waters are magnetic is not borne out by careful tests, and, in fact, the existence of magnetic water, although frequently asserted, has never been proved at any locality in this country or any other.

MILFORD.[1]

The public supply of Milford is obtained from three wells driven in 1903 in the alluvium of Little Miami River just above the town. The wells are so situated that pollution is very improbable, and the public supply is to be preferred to that from private wells in the town. An analysis is given in the tables, pages 200–201, and further particulars of the supply will be found on page 51.

NEW RICHMOND.[1]

The wells of New Richmond, which is situated on a low terrace bordering the Ohio, range from 30 to 83 feet in depth, with an average of 40 feet. The wells are mainly driven, the best being sunk to the level of the river, where they generally obtain a good supply of hard water. No rock is encountered. The water-bearing sands are overlain by clayey deposits and the supplies will probably remain safe as long as privies or cesspools are not sunk to the sand underneath.

At the base of the bluff is a well, sunk about 1887 for oil and gas, the depth attained being reported as about 1,400 feet. A strong flow of salt water was encountered near the bottom, probably from the St. Peter sandstone, and a slight flow continued after a lapse of 19 years. (See analysis, pp. 200–201.)

[1] Conditions in 1906.

The public supply of New Richmond is taken from Ohio River, the water being pumped to a settling reservoir on the bluffs for treatment, after which it is distributed by gravity to the town.

WATER PROSPECTS.

For the assistance of drillers or others seeking underground-water supplies the following table showing underground-water conditions is presented:

Underground-water conditions in Clermont County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Afton	Till	15		Richmond and Maysville.	Richmond and Maysville.	Small.
Amelia	do	10	Plenty	do	do	Do.
Baldwin	Alluvium, till	30		Eden	Point Pleasant	Do.
Bantam	Till	10	Fair	Richmond and Maysville.	Richmond and Maysville.	Do.
Batavia	Alluvium, till	Deep.		Eden	Point Pleasant	Do.
Baywood	do			do	do	Do.
Belfast	Till	30+	Fair	Richmond and Maysville.	Richmond and Maysville.	Do.
Bethel	do	20	Plenty	do	do	Do.
Blairsville	Alluvium			Point Pleasant	Point Pleasant	Do.
Blowville	Till, alluvium	20		Eden (?)	do	Do.
Boston	Till	15	Fair	Richmond and Maysville.	Richmond and Maysville.	Do.
Branch Hill	Alluvium			Eden	Point Pleasant	Do.
Cedron	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Charleston		12	Plenty			
Chilo	Alluvium	70+	do	Point Pleasant	Point Pleasant	Do.
Clermontville	do	Deep.		do	do	Do.
Clover	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Craver	do	15		do	do	Do.
Edenton	Alluvium	25+	Moderate	do	do	Do.
Elenor	Till	10	Fair	do	do	Do.
Elston	Alluvium			Eden	Point Pleasant	Do.
Epworth H'g'ts	Till			Eden (?)	do	Do.
Felicity	do	10	Plenty	Richmond and Maysville.	Richmond and Maysville.	Do.
Funston	do	15		do	do	Do.
Glen Este	do	15		do	do	Do.
Glenrose	do	10	Fair	do	do	Do.
Goshen	do	20	Plenty	do	do	Do.
Guinea	do	20		do	do	
Hamlet	do	10	Plenty	do	do	
Hennings Hill	do	20		do	do	
Hillstation	Till, alluvium	20		do	Richmond, Maysville, Eden.	Do.
Hulington	Till	10		do	Richmond and Maysville.	Do.
Laurel	do	15		do	do	Do.
Lerado	do	15	Moderate	do	do	Do.
Lindale	do	10	Plenty	do	do	Do.
Locust Corner	do	20	Fair	do	do	Do.
Loveland	Alluvium		Plenty	Eden	Point Pleasant	Do.
Manila	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Marathon	do	30	Plenty	do	do	Do.
May	do	10		do	do	Do.
Merwin	do	10	Plenty	do	do	Do.
Miamiville	Alluvium			Eden	Point Pleasant	Do.
Milford	do	Deep.	Plenty	do	do	Do.
Modest	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Monterey	do	25+	Plenty	do	do	Do.
Moores Fork	do	30	Small	do	do	Do.
Moscow	Alluvium	90+	Plenty	Point Pleasant	Point Pleasant	Do.

Underground-water conditions in Clermont County—Continued.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Mount Carmel	Till	15		Richmond and Maysville.	Richmond and Maysville.	Small.
Mount Holly	do	8	Plenty	do	do	Do.
Mount Olive	do	15	Fair	do	do	Do.
Mount Pisgah	do	25	Moderate	do	do	Do.
Mount Repose	do	10	do	do	do	Do.
Mulberry	do	15	Plenty	do	do	Do.
Neville	Alluvium			Point Pleasant	Point Pleasant	Do.
New Palestine	do			do	do	Do.
New Richmond	do	75+	Plenty	do	do	Do.
Newtonsville	Till	8	do	Richmond and Maysville.	Richmond and Maysville.	Do.
Nice	do	15		do	do	Do.
Nichols	Nichols	10		do	do	Do.
Ninemile	Alluvium			Eden (?)	Point Pleasant	Do.
Ninevah	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Obannon	do	20		do	do	Do.
Olive Branch	do	9	Moderate	do	do	Do.
Owensville	do	15		do	do	Do.
Perintown	Alluvium	30+	Plenty	Eden	Point Pleasant	Do.
Pinhook	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Pleasant Hill	do	15		do	do	Do.
Point Isabel	do	20		do	do	Do.
Point Pleasant	Alluvium		Fair	Point Pleasant	Point Pleasant	Do.
Rocky Ford	do			Eden	do	Do.
Rural	do			Point Pleasant	do	Do.
Salem	Till	10	Plenty	Richmond and Maysville.	Richmond and Maysville.	Do.
Saltair	do	10		do	do	Do.
Simpkinson	do	12	Moderate	do	do	Do.
South Milford	Alluvium			Eden	Point Pleasant	Do.
Spann	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Stone Lick	Alluvium			Eden	Point Pleasant	Do.
Summerside	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Tobasco	do	15	Moderate	do	do	Do.
Utopia	Alluvium	100+	Plenty	Eden	Point Pleasant	Do.
West Woodville	do	10	Moderate	Richmond and Maysville.	Richmond and Maysville.	Do.
Wiggonsville	do	8	Fair	do	do	Do.
Williamsburg	do	20	Plenty	do	do	Do.
Willowville	do	15		do	do	Do.
Withamsville	do	9	Plenty	do	do	Do.

CLINTON COUNTY.

By M. L. Fuller.

The underground-water investigation for the present report covered all of Clinton County except a strip about 5 miles in width along its eastern border and included all the cities and villages except New Vienna, Memphis, Lees Creek, Sabina, and Reesville.

SURFACE FEATURES.

Clinton County, although somewhat rougher than many of the other counties of southwest Ohio, consists in the main of flat upland plateaus standing at elevations of 950 to over 1,100 feet. In the southwest corner of the county, southwest of a line extending from the vicinity of Clarksville through Cuba and Martinsville to the

county boundary 3 or 4 miles northeast of Lynchburg, there is a relatively low and very flat surface commonly ranging from about 950 to 1,025 feet in altitude and but little cut by valleys, except near Clarksville. Along the line mentioned, however, a scarp or bluff rises 50 to 100 feet above this low surface, or to heights of about 1,000 feet above sea level. Back from the bluff the land again stretches northeastward as a broad flat. This flat, however, owing to its higher elevation, has been much cut by the streams into deep, sharp valleys, of which those of Todds Fork and Cowans Creek are the most striking, their channels being from 100 to nearly 200 feet below the adjacent uplands. The scarp described above lies near the outer limit reached by the latest or Wisconsin ice sheet, but the morainal deposits are not at all conspicuous and may be neglected. Another low but better-defined belt of morainal knolls crosses the county in a northwest-southeast direction midway between Wilmington and the northeast corner.

WATER-BEARING FORMATIONS.

SURFACE DEPOSITS.

ALLUVIUM.

No large rivers cross Clinton County, and the valleys, being mainly narrow, do not contain extensive deposits of alluvium, such as characterize those of the Miami and similar streams. Of the alluvial deposits, those of Todds Fork are the most important, having a breadth of half a mile and extending along the stream for 10 miles or more. Narrower deposits occur along Cowans and Little creeks, East Fork of Little Miami River, and other streams, but over a large part of the county, especially on the lower plateau to the southwest, very little alluvium is present. Near Clarksville, on Todds Fork, the alluvium probably has a depth of 50 feet or more, but at some other places on this and other creeks the streams flow on or near bedrock. Probably many old alluvial deposits occupy buried channels beneath the till, as indicated by deep wells scattered among shallow ones, but at present they can not be satisfactorily located and traced.

Where the alluvium is more than a few feet thick it usually holds abundant water in its sand and gravel layers, which are nearly always to be found in the centers of the valleys. Wells reaching to or below stream level usually get ample supplies. In many places toward the edges of the valleys rock is encountered before this level is reached, or the deposits are found to be finer and less porous, and under either of these conditions the procuring of water supplies is doubtful. Most of the alluvium of Clinton County, or at least its superficial portion, is later than the drift and contains few if any interbedded till sheets. The water rarely rises in the wells.

LOESS.

South of a line extending southeastward from a point near Clarksville through Cuba and Martinsville a coating of yellow clayey loam known as loess, varying from a few inches to a few feet in thickness, forms the surface. Farther south this material is thicker and in a few places is a factor in the water supply. In Clinton County, however, it is of no importance in this connection.

TILL.

The line from Clarksville through Cuba and Martinsville, just mentioned, also separates the pebbly clay or till into two parts, one thinner and older to the south and the other thicker and in part newer to the north. The thin sheet coincides in area with the lower plateau plain and ranges in average thickness from less than 10 feet along the southern border of the county to 30 feet or more along the Clarksville-Cuba line. Depths to rock of more than 70 feet are reported in some wells, but these wells appear to have been sunk in old buried chanels.

Northeast of the Clarksville-Cuba line the till abruptly thickens, forming the bluff described (p. 89). Near the edge the rock is usually 100 feet or more below the surface, but it appears here and there in valleys, as at Ogden, Todds Fork, and west and north of Wilmington, and in the eastern part of the county is not generally far below the general surface of the upland. Both till sheets are very clayey in Clinton County and do not contain so many sand and gravel layers as in the counties to the northwest.

Owing to the thinness of the deposit of the older till in the southeastern portion of the county water is not abundant in it and in a large number of wells can not be obtained short of rock, especially at Blanchester and vicinity. Where the till is 20 feet or more thick wells generally get fair supplies, but in many places, owing to the absence of gravelly layers, drilled and driven wells are unsuccessful. Many open and tubular wells sunk on the uplands or bluffs near the deep valleys and ravines which are so numerous in the western portion of the county are likewise unsuccessful, owing to the readiness with which the water drains away. On the whole the till is a decidedly less satisfactory source of supply in Clinton County than in the counties to the north and west.

MORAINAL DEPOSITS.

Morainal deposits are not very extensively developed in Clinton County, being limited to two belts that are of no great thickness. As in adjoining counties, they are in general prevailingly gravelly

and readily permit the water to drain outward or to sink into underlying deposits. For this reason they are of no importance as a source of water.

ROCK FORMATIONS.

NIAGARA LIMESTONE.

Owing to the thickness of the drift over the region of its contact with the next lower formation the margin of the "Niagara" can be only approximately located. It probably enters the county nearly north of Wilmington and extends a little east of south to the county line between New Vienna and Lynchburg, passing east to Wilmington. The boundary is not regular, the formation extending farther westward in the highlands between the streams than in the valleys. Its lower layer, as seen resting on the "Clinton" limestone on Todds Fork, is a blue shale a foot or two thick, overlain by 12 to 15 feet of compact limestone suitable for local building purposes. Above this is a loose, porous limestone with many cavities. This series underlies the greater part of the county to the east, except at Snow Hill, some miles south of New Antioch, where higher and even more porous and friable beds are found. The total thickness of the "Niagara" in this county is probably not over 75 or 100 feet.

"CLINTON" LIMESTONE.

The "Clinton" limestone is a gray or pinkish granular limestone, massive or irregularly bedded, and 25 to 30 feet or more in thickness. Its outcrop lies just west of that of the "Niagara," and, being lower down, is much more irregular, following the complicated windings of the drainage system. It is exposed on Todds Fork at intervals from a point northwest of Ogden to a point north of Wilmington, here and there on Cowans Creek and its branches as far east as New Antioch, and at points a short distance northeast of Martinsville and south of Farmersville (Pl. I). Although its outcrops are numerous it does not form lines of conspicuous bluffs along the stream, as it does in certain of the counties both to the north and south.

The "Clinton" limestone, except in the valley bottoms, is generally covered with a considerable thickness of drift, and in such situations is not commonly used as a source of supply, although it probably carries considerable water. Some of the deeper wells of the higher uplands in the vicinity of New Antioch, Martinsville, and Farmersville, however, possibly draw from it. Its outcrop is so deeply covered in Clinton County that it does not usually give rise to springs, as it does in counties to the north.

RICHMOND FORMATION.

Much of the Richmond formation exposed in Clinton County is shaly, and varies from yellowish green to blue in color. It lies at an average depth of 10 to 30 feet beneath the lower plateau plain southwest of the Clarksville-Cuba-Martinsville Bluff, and is seen in the valleys of Todds Fork, Lytle and Cowans creeks, Little East Fork, and at places near the western edge of the county. Locally the stream bluffs, some of which are nearly 100 feet high, consist mainly of the rocks of this formation.

The Richmond formation is not a good water bearer. Many wells, even of the dug type, obtain only small supplies from it, and drilled wells are rarely successful. Where the drift is very thin, however, it is the only available source, and trial wells must be sunk until one yielding sufficient water is found.

DEEPER ROCKS.

Two wells, sunk to depths of about 1,500 feet at Lynchburg, failed to obtain water in any amount, indicating the futility of sinking to the deeper beds for water.

SUMMARY AND RECOMMENDATIONS.

In many ways the ground-water supplies of Clinton County are unsatisfactory. The drift carries less sand and gravel than at many other points, the alluvial deposits are restricted to narrow valleys, and the rocks, especially those of the Richmond formation, carry but little water. Under such conditions open wells afford the best supply. Drilled wells, because of their small size, not only fail to tap many of the small seeps, but afford no opportunity for storage. Wherever possible alluvium should be utilized. Next to this the drift will, in general, afford the best supplies, but in the area of the "Niagara" limestone waters can generally be obtained from the rock. No deep beds, affording water suitable for domestic, public, or industrial supplies, exist, and deep drilling should be avoided.

NOTES BY TOWNS.

BLANCHESTER.[1]

The problem of water supply in Blanchester is acute, owing to the thinness of the drift deposits, from which at other points water is usually obtained in relative abundance. Not only is the drift thin, but the underlying Richmond formation, which is in many places within 10 or 15 feet of the surface, is one of the poorest water bearers of southwestern Ohio. Fortunately, however, the region is relatively flat and the underground drainage slow, so that more or less water is

[1] Conditions in 1906.

held back in the thin till and in the upper part of the rock. Drilled wells rarely obtain large supplies, but dug wells carried to depths of 40 feet or more, on account of their large storage capacity, usually yield enough for ordinary domestic use. To insure safety from pollution, however, the shallow water in the drift and upper part of the rock should not be utilized; the well should be walled up and cemented from the surface to a level 3 to 5 feet below the top of the rock. Cisterns can be made to yield enough for ordinary demands, but to do this they should be not less than 10 feet in diameter and 15 feet deep and should have absolutely tight walls. The ordinary 6 by 10 foot cistern often fails when it is most needed because of its small storage capacity. Many cisterns develop cracks that permit leakage. This should be guarded against by frequent inspection.

An attempt was made at Blanchester in 1896 to procure water from three dug wells, 50 feet in depth and 6 feet in diameter, but, as was to be expected from the nature of the geologic formations, the supply was entirely inadequate for public purposes, and it was necessary to construct an artificial impounding reservoir in a shallow draw. The entire supply is derived from surface water collected in a settled and farming region and is not only offensive in odor and taste but unsafe to the health. Fortunately, however, no attempt is made to use it for domestic purposes.

CLARKSVILLE.[1]

Clarksville is located on the south side of the valley of Todds Fork, a part of the town being on the lower slopes. Owing to the fact that the stream is flowing in a comparatively recently developed valley, with only a thin coating of alluvium over the underlying till or rock surfaces, water is more difficult to obtain here than at most points in the larger stream valleys. Instead of finding extensive alluvial gravels, many of the wells penetrate blue clay or till or enter the scantily water-bearing Richmond formation within a short distance of the surface.

The town is badly in need of a public supply to afford adequate fire protection and to replace the unsatisfactory wells. An inspection of the vicinity leads to the belief that a system of driven wells across the valley just above the town would yield the necessary water.

CUBA.[1]

Cuba is situated on a sloping hillside of unconsolidated material. Many of the houses are located on the east-west pike running parallel with the slope, but others are on the hillside above. All the drainage from the privies and sinks enters the soil and moves downward

[1] Conditions in 1906.

toward the valley, more or less seriously contaminating the wells along the main street. The water of the public well at the crossroads in the center of the town is believed to be badly polluted. Tightly cemented cisterns of sufficient size to provide a supply for the whole year are suggested as a safe substitute for the questionable wells.

M'KAY.[1]

McKay shows somewhat exceptional underground-water conditions. The drift, although apparently more than 100 feet in depth, consists almost entirely of blue clay, the usual gravelly beds being entirely absent. Very few first-class wells are obtained either from the drift or from the underlying rock, although some fair dug wells from 12 to 25 feet in depth are found. The following is a record of a 175-foot well:

Record of well at McKay.

	Thickness.	Depth.
	Feet.	*Feet.*
Drift: Blue clayey till	110	110
"Clinton" limestone: Limestone	8	118
Richmond formation:		
Red shale	7	125
Blue shale	50	175

MARTINSVILLE.[1]

The conditions in the vicinity of Martinsville are variable and uncertain. Near the railroad at the lower side the creamery and other wells get considerable water, but on the plateau on which the town is situated several wells have been unsuccessful, though some were carried to a depth of 115 feet. In general, although many shallow dug wells procure small supplies, water is notably short on the slopes and crest of the ridge. More water, however, is to be had on the flats just south of the town, few farms there having trouble with their supplies, which they obtain from gravelly beds in the till. In some places where water is scarce several wells have been connected and pumped by a windmill with good results. In the Martinsville region little is to be hoped from drilled wells in the rock, nearly all rock wells being either failures or only partial successes.

NEW BURLINGTON.[1]

On the bank of West Fork of Mill Creek, about half a mile southeast of New Burlington, a very peculiar well yields two different types of water from different depths. The well is dug 36 feet and drilled 12 feet. The rocks consist of limestone, with perhaps 30

[1] Conditions in 1906.

per cent of shale, and lie at the Richmond-Maysville horizon. Water stands 8 feet below the surface. There are two pumps in the well; the pipe of one extends 16 feet below the surface and that of the other 35 feet below, or within 8 inches of the bottom of the dug part of the well. The shorter pipe obtains fresh water and the longer one very strong salt water. The fresh-water bed is 8 feet below the surface; the salt-water bed 21 feet below it. The salt water is reported to have been used for medicinal purposes at various times. The analyses of these two types of water are given on pages 200–201.

WILMINGTON.[1]

Wilmington is situated on a broad drift plain formed mainly of blue clay or till. Most of the people not using the public supply depend on shallow dug wells, although a few use dug wells as much as 60 feet deep, or drilled wells, some of which are reported to be 172 feet deep. The shallower wells get water in the blue clay and the deeper ones from a gravel bed in or beneath the clay. It is said that no rock is encountered in the town, although it comes to the surface a short distance to the north.

A deep well drilled in 1887 for oil and gas afforded the following partial record:

Record of deep well at Wilmington, Ohio.[a]

	Thickness.	Depth.
	Feet.	*Feet.*
Drift	84	84
"Niagara" limestone: Shale	4	88
"Clinton" limestone:		
Red rock fossil iron ore	3	91
Limestone	15	106
Richmond formation:		
Brown shales	5	111
Shale	850	961
Eden shale and Point Pleasant formation: Shale interbedded with limestones	[a] 250	[a] 1,211
"Bird's-eye" limestone.		

[a] Orton, Edward, Geol. Survey, Ohio, vol. 6, 1888, p. 296. The geologic formations are the interpretations of the authors of this report. The thickness of the Eden shale and Point Pleasant formation is not given in the published record, and to complete the record the approximate thickness in the well at New Vienna is inserted.

Wilmington is to be regarded as fortunate in procuring a supply from wells in a region where neither the drift nor the rocks commonly carry water in any considerable amounts. The supply is obtained from five deep wells owned by the Wilmington Water & Light Co., sunk to a gravel below the till in the eastern part of the town. The water appears to be safe and is to be preferred to that from private wells. So far, the supply seems to be sufficient for the needs of the town.

[1] Conditions in 1906.

WATER PROSPECTS.

The following table summarizes the more important facts concerning underground-water conditions at the principal villages and towns covered by the field work in Clinton County:

Underground-water conditions in Clinton County.

Towns.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Blanchester	Till	10	Small	Richmond	Richmond and Maysville.	Small.
Burtonville	do	75	Plenty	"Clinton" (?)	"Clinton" (?)	Plenty?
Clare	do	100+	Small	Richmond	Richmond and Maysville.	Small.
Clarksville	Alluvium moraine.	Deep.	do	do	do	Do.
Clinton	Till	75+		"Niagara"	"Clinton"	Usually plenty.
Cuba	Till, moraine	140+	Plenty	Richmond	Richmond and Maysville.	Small.
Deserted Camp	Till	75		"Niagara"	"Clinton"	Usually plenty.
Farmers station.	Moraine	35		"Niagara" (?)	"Clinton" (?)	Plenty?
Gurneyville	Till	100		Richmond	Richmond and Maysville.	Smal .
Kingman	do	58+	Small	do	do	Do.
Lees Creek	do	30		do	do	Do.
Little Center	do	100		do	do	Do.
Lumberton	do	100+		do	do	Do.
McKay	do	100+		do	do	Do.
Martinsville	Till, moraine	40	Moderate	do	do	Do.
Melvin	Till	10		"Niagara"	"Clinton"	Usually plenty.
Midland	do	14	Moderate	Richmond	Richmond and Maysville.	Small.
Morrisville	do	100+		"Clinton" (?)	"Clinton" (?), Richmond and Maysville.	Moderate.
New Antioch	do	75		"Niagara"	"Clinton"	Usually plenty.
New Burlington.	Alluvium	65+		Richmond	Richmond and Maysville.	Small.
New Vienna	Till	40	Moderate	"Niagara"	"Clinton"	Usually plenty.
Oakland	do	110+	do	Richmond	Richmond and Maysville.	Small.
Ogden	Alluvium	20	do	do	do	Do.
Pansy	Till	30		do	do	Do.
Port William	do	10		"Niagara"	"Clinton"	Usually plenty.
Reesville	do	20		do	do	Do.
Sabina	do	64		do	do	Do.
Sligo	do	100	Small	Richmond	Richmond and Maysville.	Small.
Westboro	do	12	Moderate	do	do	Do.
Wilmington	do	75+		"Niagara"	"Clinton"	Usually plenty.
Vandervorts Corner.	do	75+		Richmond	Richmond and Maysville.	Small.

DARKE COUNTY (SOUTHERN).

By Frederick G. Clapp.

SURFACE FEATURES.

The part of Darke County included in this report ranges in elevation from 1,000 feet along Millers Fork and on the branch of White Creek to over 1,220 feet on some of the hills in the western part of the county. The area may be said to consist in general of three types of surface—(1) broad, gently undulating plains, which form

by far the greater portion of the whole; in this type of surface hills over 20 feet high are rare; (2) a belt of north-south morainal hills, rising 100 feet or more above the surface of the clay plains and valleys on which they rest and crossing the western edge of the area; this region is very undulating; (3) the valleys of a few small creeks, from a few feet to 100 feet or more below the surrounding country and from a few feet to one-fourth mile broad.

Except in a few localities, rock is not exposed at the surface, but is buried under a few feet to nearly 300 feet of sand, gravel, and till. The underlying rock surface is known from well records to be very irregular and to bear no relation to the form of the present surface.

WATER-BEARING FORMATIONS.

By M. L. Fuller.

SURFACE DEPOSITS.

ALLUVIUM.

The material classed as alluvium includes that deposited by streams in present or former valleys. It ranges from coarse gravel to fine clay and silt. The silt commonly forms the surface of the present flood plains of the creeks and the other deposits lie underneath. Alluvial deposits not only include those of the present-day streams, but they underlie large areas of till plains, where they help to fill valleys that are now deeply buried but that existed as true valleys before the glacial epoch. These buried alluvial deposits, which are generally reported by well drillers as sand or gravel, commonly constitute the water-bearing gravels in the regions covered by till. Many of them were probably laid down as outwash deposits during the closing part of the earlier of the two glacial stages.

With the exception of the dug wells in till the great majority of wells in southern Darke County obtain their supplies in the alluvial sand and gravel deposits buried underneath till. The waters are hard but otherwise good. The till acts as a surface covering and prevents pollution by surface water.

TILL.

The material which forms the surface over most of southern Darke County and which makes up a large bulk of the deposits lying above bedrock is a hard, pebbly clay known as till. This material forms the greater part of the broad flats covering a large area in this county and is also abundant in the valleys and the areas of morainal deposits. From well records and from general geologic conditions it is believed

to occur, where deep, in at least two different layers, each representing a glacial stage.

Many cliffs along the creeks and elsewhere show the character of the till. It is uniformly very hard and tough and generally pebbly. Its normal color is blue-gray, but in its upper few feet it is everywhere weathered to a buff. Water is not abundant in the till on account of its clayey and generally impervious nature, but perhaps a dozen wells in southern Darke County obtain small amounts from somewhat sandy lenses. The water in the till itself is of rather poor quality and is frequently contaminated by surface drainage. All good wells go through the till into underlying gravels or rock.

MORAINAL DEPOSITS.

The morainal deposits of Darke County are mostly confined to the portion west of New Madison. They are very hilly, are much cut up by ravines, and in places have what is known as the kettle-hole type of surface—that is, they contain small depressions without any outlets. The moraines are composed largely of sand and gravel, but contain also some irregularly intermixed pebbly clay or till. In places large numbers of bowlders, some of them several feet in diameter, cover the surface. These are sometimes struck in wells and are mistaken for bedrock.

Water is generally present in morainal deposits, but the heterogeneous mixture of sand, gravel, clay, and till, and the extremely undulating surface of the deposits make the depth to it uncertain. One well is said to have gone more than 200 feet before striking bedrock and to have found little water. This, however, represents an extreme case, for plenty of good water will generally be found within 100 feet of the surface.

ROCK FORMATIONS.

Rock outcrops in only one or two places in Darke County. Elsewhere it is buried beneath great depths of drift and is reached by only a moderate number of wells. So far as known the rock consists of the "Niagara" limestone from 100 to several hundred feet thick, underlain by the "Clinton" limestone and the Richmond and Maysville formations. The "Niagara" limestone is very hard, but contains numerous small solution passages through which water circulates. These may be tapped by the drill and good wells obtained. Some wells fail through reaching the bottom of the limestone without striking any of these water-bearing passages, but most of those to the "Niagara" are successful. Many of them penetrate the rock only a few feet. The water is of excellent quality and not so liable to pollution as that in the drift.

NOTES BY TOWNS.

ARCANUM.[1]

The waterworks of Arcanum consist of six wells 38 to 80 feet in depth and 8 inches in diameter, drilled on the plain at the southeast corner of the village. The plant was installed in 1906. The wells entered rock at 36 feet, and most of the water was encountered within 2 feet of the top of the rock. The water rises within 10 feet of the surface.

About a dozen wells have been drilled for gas at Arcanum, and some of these have met with success. No records were kept, but their maximum depth is believed to be about 1,200 feet. Gas was obtained in the "Birdseye," and the successful wells have been productive for 15 years. Little or no salt water is reported to have been found.

GORDON.[1]

At Gordon several small flowing wells situated along a small valley constitute an interesting feature. The wells consist of 1¼-inch pipe driven about 13 feet to rock. The water overflows at about a gallon a minute in a constant stream 2 feet above the surface. The head is derived from the slight rise of the surface deposits a few hundred feet to the east.

WATER PROSPECTS.

The following table shows the general underground-water conditions at each of the more important localities in southern Darke County:

Underground-water conditions in southern Darke County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rocks nearest surface.	Water-bearing rock.	Water supply.
		Feet.				
Arcanum	Till	27–36	Moderate	"Niagara"	"Niagara" and "Clinton."	Usually plenty.
Gordon	do	92	do	do	do	Do.
Ithaca	do	8–30	do	do	do	Do.
New Madison	do	28–50	do	do	do	Do.
Savona	do	115	do	do	do	Do.

[1] Conditions in 1906.

GREENE COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

The surface features of Greene County differ considerably in different parts. East of a north-south line drawn approximately through the center the surface is prevailingly high and, although cut by many valleys, is marked by rather wide stretches of relatively flat uplands between the streams. West of the line are the broad, deep valleys of Little Miami River and Beaver Creek and the sharper but still deeper valleys of their tributaries. In the northwest corner is a considerable area belonging to the valley of Mad River. From 100 to 200 feet above the streams are flat plateau remnants similar to though much smaller than those east of the Little Miami. The elevation of the valleys is usually from 800 to 850 feet, and that of the uplands ranges from 950 feet in the western part of the county to 1,100 feet in the east. The larger valleys, such as those of Little Miami River and Beaver Creek, are broad and open, but many of their tributaries head in deep, cliff-walled ravines, marked by picturesque waterfalls. Good examples of such ravines may be seen at Yellow Springs and Clifton.

WATER-BEARING FORMATIONS.

In Greene County alluvium, pebbly clay or till, and morainal materials constitute the chief surface deposits and "Niagara," "Clinton," and "Richmond" the chief rock formations.

SURFACE DEPOSITS.

ALLUVIUM.

The principal area of alluvial deposits is in the Mad River valley, at the extreme northwest corner of the county. This valley is 2 miles or more in width and contains many square miles of alluvium. In character the deposits are prevailingly gravelly, but interbedded with the gravels or overlying them in places, especially near the sides of the valley, is more or less till. In some places knolls of till project through the gravel surface. The valleys of Beaver Creek and of Little Miami River are locally of considerable width and contain important deposits of alluvium. The alluvium on Beaver Creek is connected with and partakes of the character of the deposits in the Mad River valley, both being largely the work of earlier streams or of earlier stages of the same stream. The alluvium of the Little Miami is to a somewhat greater extent the work of the present stream. The valleys of the smaller streams are not generally very

wide nor their deposits extensive. As in adjacent counties, considerable alluvium doubtless exists in buried channels beneath the till.

Abundant water can be procured from the alluvium at almost all points, but the depth to it varies considerably, according to the elevation of the surface. On the lower bottoms near the streams water is often found at the level of the stream at depths of 10 to 15 feet, but farther back, where the surface rises to low terraces, the depths to water are somewhat greater. The wells on some of the low swells and knolls, although surrounded by alluvium, are themselves in till. A few wells starting in alluvium encounter till a short distance below the surface, but the water in these is scanty, and most wells must go considerably deeper for their supplies.

TILL.

The till, which is a yellowish pebbly clay at the surface, grades downward into blue clay at depths of 10 to 15 feet. It forms a mantle over the whole surface except in the alluvium-filled valleys, burying the rocks to depths of a foot to 50 feet or more. The variation in depth to rock is due mainly to the inequalities of the rock itself, the till surface being rather flat. The till is thinnest along the sides of the valleys, near which in many places the rock outcrops. Back from the valleys the drift gradually thickens, reaching 25 to 50 feet on the general uplands and being thicker over buried valleys. At Wilberforce it measures over 75 feet and at Bowersville 50 to 75 feet. There appear to be some sand and gravel layers in the till, but they are less numerous than in the counties to the northwest.

As would be expected from the scarcity of gravel and sand layers, the water supplies of the till are not so abundant as in areas where such layers are common. There is usually, however, enough water, even in the more clayey areas, for ordinary domestic and farm purposes, providing the till has a thickness of 20 feet or more. Where it is thinner than this the supplies are likely to be scant. This is especially true in Cedarville and Miami townships.

MORAINAL AND OTHER GRAVELS.

Two north-south belts of morainal deposits occur in Greene County, one along the eastern boundary and another just east of Xenia. The drift knolls constituting these belts are not very high and contain more pebbly clay and less gravel than are commonly found in moraines. Besides the morainal drift numerous more or less sheetlike deposits of sand and gravel occur, representing the outwash from the glacial ice during its retreat from the region and being in fact a glacial alluvium located on the uplands instead of the

valleys. It is possible that in part at least the deposition took place in temporary glacial lakelets.[1]

The morainal belts, being composed either entirely of till or of a thin gravel spread over the surface, do not differ greatly from the pebbly-clay uplands as to their water supplies. The gravels and sands, because of their elevated position and the readiness with which they are drained, are not important sources of water, it being usually necessary for wells to penetrate to the underlying till.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

The "Niagara" limestone, the highest and youngest of the rock formations of Greene County, forms the surface beneath the drift over the entire eastern half. Its western boundary enters the county from the north just east of Osborn, passes with some irregularities southward to the vicinity of Byron, and then swings around to the east and up the valleys of Little Miami River and Clark and Massie creeks, whence it passes southeastward just east of Xenia, leaving the county in the center of Cæsars Creek Township. An outlier also appears on the highlands of southwestern Beaver Creek Township. In fact, the "Niagara" in Greene County is distinctly an upland formation.

In character is varies considerably in the different beds. At the base, separating it from the underlying "Clinton," is about a foot of blue clay. Over this comes a layer of bedded limestone, suitable for quarrying and as much as 10 feet in thickness. This is overlain in succession by 30 feet of shale and 85 feet or more of blue and drab massive to bedded limestone, making a total thickness of about 125 feet.[2] In Cedarville and Miami townships it is very near the surface, the rocks outcropping as cliffs along many of the ravines and being barely covered at numerous other points, as at Yellow Springs, Clifton, and Cedarville. Elsewhere the drift is in many places of considerable thickness.

The "Niagara" of Greene County carries considerable quantities of water and gives rise to a great number of springs. These emerge at two levels. The upper is at a thin shale parting 60 or 70 feet above the base of the formation and in general is less important as a spring horizon than the top of the shale bed 30 feet lower down, but the Chalybeate Spring of the Neff Grounds at Yellow Springs (Pl. IX, *B*), the most noted spring of the county and one which flows over 100 gallons a minute, occurs at this level. The springs at the top of the 30-foot shale bed are both numerous and copious, especially along the Little Miami below Clifton and on Massie Creek below Cedarville.

[1] Orton, Edward, Geol. Survey Ohio, vol. 2, 1874, p. 681.
[2] Idem, p. 668.

The lower springs, the Arctic and Magnetic of the Neff Grounds (p. 107), belong to this horizon. A few springs occur at the blue-clay parting between the "Niagara" and "Clinton" limestones.

Wells sunk into the "Niagara" limestone usually get fair supplies if carried to the 30-foot shale bed, along the top of which the water collects. Some shallow wells get water from the upper shale parting, but the supplies are small and not permanent.

"CLINTON" LIMESTONE.

The "Clinton" limestone is semicrystalline, is largely pinkish or reddish in color, and has a thickness varying from 25 feet near Spring Valley to 50 feet near Yellow Springs. It is irregularly bedded and is prevailingly sandy near its base. Its outcrop extends along the western border of the "Niagara" and occurs as outliers at short intervals along the western border of the county south of the Mad River valley. The outcrops in the vicinity of Mad River are extensive, and others occur at many points near Xenia, on Oldtown River, on Massie Creek, at the head of Ludlow Creek, etc. The "Clinton" is marked at several points by sink holes into which a few streams disappear, as near the junction of the Xenia-Fairfield and Dayton-Yellow Springs pikes, to reappear elsewhere as large springs.

The "Clinton" limestone carries much water in the form of underground streams occupying channels dissolved in the sandy and more soluble basal layers at the contact with the impervious shales of the underlying Richmond. Among the more important springs at this level are those at the head of Ludlow Creek and at Goes station. Most wells sunk to the same horizon would doubtless procure considerable water, but the supplies are no greater than those in the overlying "Niagara," and it is therefore seldom worth while to sink to the deeper bed for the supply.

RICHMOND FORMATION.

The Richmond formation underlies the drift and alluvium in the lower portions of the county, or in the area west of the outcrop of the "Clinton." Its upper part consists of a 25-foot bed of fine shale, bluish or reddish in color, lying just below the "Clinton" at Goes and elsewhere. Below this lie the usual alternations of thin layers of bluish limestone and shale, the total exposed thickness of these layers in the county being about 250 feet. Although it doubtless contains some water, the Richmond formation is far less important as a water bearer than the overlying limestones, and except where these beds and the water-bearing alluvium and drift are all absent, it will rarely be advisable to drill for water in the formation. Its chief importance is as an impervious bed concentrating the water in the overlying "Clinton."

NOTES BY TOWNS.

CEDARVILLE.[1]

The first deep well in the vicinity of Cedarville was sunk near the site of the Hager paper mill 25 years ago in search of oil and gas, reaching a depth of about 1,500 feet. A heavy stream of fresh water was encountered at about 250 feet. The well failed to obtain oil or gas and was later plugged at about 300 feet, and a deep-well pump, afterwards replaced by an air-lift system, was installed for raising the water for use in the manufacture of paper at the works of the Hager Straw Board & Paper Co. From 150 to 200 gallons a minute was obtained, the water standing under this draft at 75 feet below the surface.

In 1903 two additional 8-inch wells were sunk to a depth of 400 feet. Water was encountered at the same depth as in the original well, apparently coming from the same seam, as the pumping of one immediately affected the level of the others, and no additional supply was obtained. The wells are used only in dry seasons, the creek furnishing the supply at other times. The well water (see analysis, pp. 200–201) is distinctly harder than that of the creek. The drill is reported to have dropped some distance when the water seam was encountered, apparently indicating an open channel in the limestone.

The town of Cedarville is located on "Niagara" limestone, the rock in many places being almost at the surface. It is full of fissures, some of which conduct matter from privies, barns, etc., directly to the wells, badly contaminating some of them and increasing the danger of typhoid fever.

The cost of drilling deep wells and of properly casing them prohibits their construction by private parties, and it is highly desirable that some sort of a public supply be installed at the earliest possible date. The best water supplies would be those from alluvium (see p. 41), but, unfortunately, the creek at Cedarville flows on or near bedrock, and no deep deposits of alluvium occur. The next best supplies would be afforded by the gravelly or sandy layers in the pebbly clay or till (p. 43), but these also are very poorly developed at Cedarville, being represented by only the few feet of soil overlying the bedrock. A drilled well would probably find water similar to that in the paper-mill well at a depth of 250 to 300 feet, but if it does not it will be useless to go deeper, as the underlying rocks are not water bearing, and some form of surface supply must be installed instead. If a deep well is sunk, the casing should on no account be stopped at the rock surface, but should be carried to not less than 150 to 200 feet, to shut off all possibility of pollution through the crevices mentioned.

[1] Conditions in 1906.

CLIFTON.[1]

What has been said of the conditions at Cedarville applies with equal force at Clifton, which is similarly situated on a limestone outcrop. Few towns have suffered more from cholera and typhoid than this, some epidemics, like the cholera epidemic of 1849, sweeping the town with disastrous effect. Most of this could have been avoided if pure water had been available.

The most promising source of water for a public supply is the thick clayey and gravelly deposit on which the higher part of the town is located. A well located 300 feet or more from any house and carried to the rock would probably obtain safe water, although several wells might be required to yield the necessary amount.

GOES.[1]

The "Clinton" limestone, which comes to the surface at Goes, gives rise to an unusually large number of fine springs on the hillsides above the village. Other good springs occur along the river; in fact, the springs are so abundant that they form the chief water supply in this vicinity. One was long used by the railroad; others supply the boilers, houses, and works of the Miami Powder Works; and many others supply private families.

JAMESTOWN.

A well, reported to be 1,776 feet deep and known as the "1776 well," was sunk in Jamestown some years ago in search of oil and gas. None was found, but a strong sulphosaline water, termed the "1776 water," was obtained and later put on the market for medicinal purposes. A partial analysis is given on pages 200–201.

OSBORN.[1]

A deep well sunk at Osborn during the oil boom 25 years ago reached the "Birdseye" limestone at 990 feet, or 170 feet below sea level. A record is given below:

Record of deep well at Osborn, Ohio.[a]

	Thickness.	Depth.
	Feet.	*Feet.*
Drift	207	207
Blue shale (Richmond and Maysville)	500	707
Darker shale (Eden shale)	213	920
Gray rock (Point Pleasant formation)	70	990
Hard crystalline limestone ("Birdseye").		

[a] Orton, Edward, Geol. Survey Ohio, vol. 6, 1888, p. 290. Correlations by M. L. Fuller.

Gas was obtained at 750 to 850 feet, but no water seams of importance are recorded.

The public waterworks, which were installed in 1895, are operated in connection with the electric-light system. The water is obtained

[1] Conditions in 1906.

from alluvium at the north end of town at a depth of about 50 feet, an overlying layer of clay preventing the access of polluting matter to the water-bearing gravel. Other particulars will be found in the table on page 51.

PAINTERSVILLE.[1]

The wells near Paintersville are of interest as affording flowing water. The supply comes from a dark sand or gravel, locally known as "black" sand, occurring beneath a bed of clay at depths of 35 to 140 feet. In about half a dozen wells the water flows freely at the surface, but apparently will not rise much above it.

SPRING VALLEY.[1]

A well sunk at Spring Valley during the oil boom is said to have reached a depth of 1,460 feet and to have obtained a large amount of saline water. The "Birdseye" was reached at about 850 feet, or 100 feet below sea level. Neither oil nor gas was obtained. The principal seam of fresh water was found at 165 feet. The water has in late years been placed on the market by the Spring Valley Medicinal Water Co.

WILBERFORCE.[1]

Wilberforce is the site of a number of institutions of learning. The scattered residences depend on wells for their water, but the college buildings are supplied by a good-sized spring in an adjoining ravine. The spring is inclosed by cement walls and protected by a spring house, the water being pumped to the buildings on the plateau above by a gasoline engine.

XENIA.[1]

A number of deep wells have been drilled at or near Xenia. The record of one of them, drilled in 1887 by the Xenia Gas Co., is given below:

Record of deep well at Xenia, Ohio.[a]

	Thickness.	Depth.[b]
Drift:	*Feet.*	*Feet.*
Clay	6	6
Gravel	20	26
Sand	35	61
Quicksand	25	86
Cemented sand	8	94
Richmond formation: Light-colored shale, etc	210	.....
Maysville, Eden, and Point Pleasant formations:		
Dark shale	325	.....
Black shale	32	.....
Shell rock	2	.....
Black shale	114	1,040
"Birdseye" limestone (penetrated)	160	1,200

[a] Orton, Edward, Geol. Survey Ohio, vol. 6, 1888, p. 290. The identifications of geologic formations are by the author.

[b] The thickness of the formations above the "Birdseye," as published in the record, add up only to 777 feet, indicating the presence of unrecorded strata having a thickness of 263 feet, the position of which is not known.

[1] Conditions in 1906.

The record gives the depth to the top of the "Birdseye" as 1,040 feet, which would place it about 170 feet below sea level at this point.

The first public supply in Xenia, owned and operated by the Xenia Water Co., was installed in 1887, the water being obtained by impounding the run-off of several springs 1½ miles north of the city. Some surface water also entered the reservoir. Later a large well was sunk through the surface coating of till into the underlying gravel. From this the water was conducted to a receiving well at the reservoir, and both reservoir and well water pumped to the standpipe. The springs supply about 300,000 gallons and the well 100,000 gallons daily.

Since 1896 six 6-inch wells, six 8-inch wells, and two 10-inch wells, located southwest of the city and penetrating a bed of gravel below the till to depths of 28 to 40 feet, have been added to the system. About 25,000 gallons daily is obtained from these wells in wet seasons. A test well sunk in the rock to 315 feet found the seams to be filled with clay, and the small amount of water obtained tasted rank and oily. Two 150-foot wells at the old station likewise proved to be failures. An analysis of the public supply is given in the table on pages 200–201.

YELLOW SPRINGS.[1]

Yellow Springs has long been noted for its mineral waters. Even in the time of the "mound builders" it was much frequented, as is attested by the mound near the Chalybeate Spring, in the Neff Grounds, and by the deep pits sunk in the limestone. The old trail between the Indian villages of the Miamis, at Oldtown and at Mad River, below Springfield, passed the spring and glen. Early in the last century the spring was selected as a site for the socialistic experiment of Robert Owen, and a building was begun, but the locality was soon abandoned in favor of another at New Harmony, Ind. For many years after the Civil War Yellow Springs was a popular resort, and a hotel accommodating 500 people was built here in 1870. In later years more northern resorts drew away most of the visitors, and in 1901 the hotel was demolished. At present the springs are developed as a recreation park (the Neff Grounds), which caters to those caring for the natural scenery and water rather than for more artificial attractions.

The natural attractions include a wooded park, bordered by high limestone bluffs of "Niagara" limestone, the Chalybeate, Arctic, and Magnetic Springs, and a picturesque lake of 5 or 6 acres fed by springs. The Chalybeate (see Pl. IX, *B*) is the principal spring of the park. It issues from the "Niagara" limestone with a volume of about 100 gallons a minute and flows over a broad expanse of moss-covered tufa, plunging over the edge into the valley below

[1] Conditions in 1906.

(Pl. IX, *A*). The tufa mass, which is some hundreds of feet across and 20 feet or more thick, is not the least interesting feature of the park. It represents the accumulation of mineral matter brought out in solution by the spring in the course of centuries and deposited over the ground and the surface of grass, leaves, and twigs, a process which may still be seen in actual operation. The tufa varies considerably in composition, some parts carrying much more iron than others. Analyses of both the iron-bearing tufa and of the purer type are given below; an analysis of the water will be found on pages 200–201.

Analyses of tufa at Yellow Springs, Ohio.[a]

	Ferruginous.	Calcareous.
Carbonate of calcium	92.97	97.60
Carbonate of magnesium	2.42	1.21
Oxide of iron and alumina	3.80	.....
Silica	.80	.60

[a] Geol. Survey Ohio, vol. 2, 1874, pp. 678, 692.

Besides the deposit at the Chalybeate Spring, other accumulations of tufa, or "red bank," as it is called locally, are found at other points in the park, especially on the east side of the lake a few hundred yards above the main spring.

The Arctic Spring is situated at the base of the bluff on the east side of the lake and has a flow of about 5 gallons a minute. The Magnetic Spring is in a ravine entering from the east about a quarter of a mile below the Chalybeate Spring, and has a flow of about 15 gallons a minute. The water of the Arctic Spring is hard, but that of the Magnetic Spring appears to be relatively soft. Neither carries any iron or any notable amount of gas.

WATER PROSPECTS.

The table below gives summaries of the underground-water conditions at the principal villages and towns of Greene County:

Underground water conditions in Greene County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Alpha	Alluvium	35+	Plenty	Richmond	Richmond and Maysville.	Small.
Bellbrook	do	30+	do	do	do	Do.
Bowersville	Till, moraine	60	.....	"Niagara"	"Clinton"	Usually plenty.
Byron	Till	30	Fair	Richmond	Richmond and Maysville.	Small.

A.

B.

SPRINGS ON NEFF GROUNDS, YELLOW SPRINGS, GREENE COUNTY.

A, Spring falling over tufa deposit; *B*, Chalybeate Spring emerging from "Niagara" limestone above a shale parting.

Underground water conditions in Greene County—Continued.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Cedarville	Till	5	Fair	"Niagara"	"Clinton"	Usually plenty.
Clifton	Till, alluvium.	5–20	Moderate.	do	do	Do.
Fairfield	Alluvium under till.	40+	Fair	Richmond	Richmond and Maysville.	Small.
Ferry	Till	25		do	do	Do.
Gladstone	Till, moraine.	75		"Niagara"	"Clinton"	Usually plenty.
Goes	Till, alluvium.	25	Plenty	"Clinton", Richmond.	"Clinton," Richmond, Maysville.	Moderate.
Grape Grove	Till, moraine.	70		"Niagara"	"Clinton"	Usually plenty.
Hawkers	Till	35		Richmond	Richmond and Maysville.	Small.
Hopkinsville	do	60		"Clinton" or "Niagara."	"Clinton"	Usually plenty.
Huffeysville	Alluvium	30+	Plenty	Richmond	Richmond and Maysville.	Small.
Jamestown	Till	40	Moderate.	"Niagara"	"Clinton"	Usually plenty.
New Jasper	do			do	do	Do.
Oldtown	Alluvium, till.			Richmond	Richmond and Maysville.	Small.
Osborn	Alluvium	30+	Plenty	do	do	Do.
Painterville	Till	140+	do	"Niagara"	"Clinton"	Usually plenty.
Roxanna	Terrace gravel.	50+	Moderate.	Richmond	Richmond and Maysville.	Small.
Spring Valley	Alluvium, etc.	30+	Variable	do	do	Do.
Trebeins	Alluvium	30+	Plenty	do	do	Do.
Wilberforce	Sandy till, moraine.	80	do	"Clinton"(?)	"Clinton"	Usually plenty.
Xenia	Till, moraine.	50	Fair	Richmond	Richmond and Maysville.	Small.
Yellow Springs	Till	5–15	Moderate.	"Niagara'	"Clinton"	Usually plenty.
Zimmerman	Alluvium, till.	90+	do	Richmond	Richmond and Maysville.	Small.

HAMILTON COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

Hamilton County is essentially a plateau, consisting of rather flat uplands lying about 500 feet above the Ohio or a little more than 900 feet above sea level. The surface, however, is not continuous but is broken by many valleys, among which are Miami, Little Miami, Mill Creek, Whitewater, and the streamless valleys connecting the Mill Creek and Little Miami valleys north of Cincinnati and the Whitewater and Miami valleys near the Butler County line, in the southwestern part of the county.

Many interesting features are presented by the valleys of Hamilton County. The main bottoms, where they join the Ohio, have an elevation of about 475 feet, agreeing approximately with that of the Ohio flats, but the tributary valleys, 10 or 15 miles back from the Ohio, generally stand at least 100 feet higher. The width of the valleys bears little or no relation to the size of the streams now occu-

pying them. For instance, the valley of the Little Miami is decidedly wider than that of the Ohio, and the valley from the Little Miami to Mill Creek, which contains no stream, is fully as wide as that of the Little Miami. Mill Creek valley near its mouth is only about half a mile in width, but above St. Bernard, where it is joined by a valley connecting with the Little Miami, it is a mile or two wide. Again, the Miami in Hamilton County flows in a narrow valley, in many places less than half a mile wide, although a broad channel 2 miles or more in width but unoccupied by any continuous stream leads westward from it just south of the Butler County line, connecting with the Whitewater Valley at the western edge of the county and extending southward to the Ohio near the Indiana State line.

These anomalous features are the result of drainage changes which have taken place in late geologic time. Originally the Ohio, instead of flowing past Cincinnati, turned northward just east of that city, flowing up the valley now occupied by the Little Miami to Newton, thence past Madison, Norwood, etc., by way of the old valley to Mill Creek. Here, turning north, it flowed past Elmwood, Wyoming, Lockwood, etc., to the Miami south of Hamilton, where it appears to have turned westward and southwestward, entering the present Whitewater Valley near the county line and flowing southward to join its present channel just west of the Indiana line. At this time, there being no east-west channel past Cincinnati, the Licking probably flowed northward across the site of Cincinnati and through the valley now occupied by Mill Creek, joining the main Ohio at St. Bernard. As the streams continued to flow in the channels indicated their beds were gradually built up by sand, gravel, etc., brought down from higher points on the stream, until a level of 600 to 640 feet above the sea was reached. The streams flowing at this level found divides across which they could cut and seek shorter courses than those in which they were then flowing, and, on the uplift of the land, the present channels were begun and have since been gradually deepened. These old valleys are of great importance with reference to underground water.

WATER-BEARING FORMATIONS.

The water-bearing beds in the surface materials include alluvium, terrace gravels, loess, till, and morainal deposits. The rock formations outcropping at the surface are the Richmond, Maysville, Eden, Utica, and Point Pleasant. Beneath these, but not outcropping, are the "Birdseye" limestone, St. Peter sandstone, Cambro-Ordovician dolomite, and Cambrian sandstone.

SURFACE DEPOSITS.

ALLUVIUM.

The alluvium occurs mainly in the larger valleys, where it varies greatly in extent, character, and depth.

In the Ohio Valley the alluvium, or those beds which constitute the flood plains of the river, occurs mainly as narrow strips ranging from a quarter to half a mile in width. To a depth of 6 or 8 feet the material is usually a sandy loam. Beneath this occurs commonly 30 feet or more of alternating beds of clay and silty sands and gravels, below which lies a thick bed of clay, including some ocher layers and sporadic tree stumps and peaty material. Beneath this again, just above low-water level, is a considerable bed of clean gravel. From low-water level to bedrock, gravel and sands commonly predominate.

The alluvial deposits of the other valleys, especially those not now occupied by large streams, differ notably from those of the Ohio. In many places beneath about 10 feet of silty soil and a few feet of sand there lies a bed of blue clay that carries some pebbles and is over 35 feet thick. Some of this blue clay is clearly of glacial origin, representing an old till. Beneath the till gravelly deposits having a thickness of about 35 feet are again encountered, and beneath these is a 25-foot bed of blue clay, with sand and pebbles, possibly representing another till. At the base in Mill Creek valley there is 43 feet of sand and waterworn gravel with a little blue clay.

In the smaller valleys and ravines entering the Ohio the alluvial deposits consist generally of coarse gravels, but the streams commonly flow near bedrock and the deposits are of no great thickness.

In addition to the alluvium of the present and abandoned river channels, already described, indications of old stream deposits exist at an elevation of about 740 feet at the north end of the village of Mount Washington and on the American Flats southeast of that town. These consist of sands and gravels containing at one locality the remains of a mastodon and other mammals. They apparently represent the channel of some small stream flowing near the crest of the uplands before the present valleys were developed.

Ample supplies of water can be obtained from the alluvium in all the larger valleys, both of the present streams and of the abandoned Ohio channels. In general, a little water is found above the clay layers, but, as these are generally well above low-water level and are quickly drained whenever the river is low, the supplies are variable. It is only when the gravels beneath the clays are reached that permanent supplies are procured. At some places in the Miami and Little Miami valleys the clays are absent and the first water is found in the gravels approximately at the stream level. Similar conditions exist in the abandoned valleys of the Ohio, except that

in places it is necessary, in order to obtain large supplies, to sink to the level of the main Ohio Valley, which is considerably below the level of the small surface streams occupying the old channels. Supplies can be obtained from the coarse gravel deposits of the small tributaries wherever the stream grade is not too steep or the rock too near the surface.

TERRACE GRAVELS.

Standing above the Ohio flood plain, which has an altitude of about 475 feet, are a number of gravel terraces rising to various elevations from 540 to 550 feet. Examples of such terraces are found at California, at Home City, and at Cincinnati. Similar terraces are present along Little Miami River at elevations from 560 to 620 feet. The terraces at Terrace Park and Milford are especially good examples. Along Mill Creek terraces rise to an altitude of over 600 feet, or more than 80 feet above the stream. These are especially conspicuous in the vicinity of Carthage, Hartwell, and Arlington Heights. Similar, though less extensive, terraces exist along the Miami. The deposits are of alluvial origin and were laid down by the Ohio when it was flowing northward at its higher level to the Miami and thence southwestward through the Whitewater Valley. These higher terraces are distinctly older than the lower ones along the Ohio, which were built by the stream at certain stages since it has been flowing in its present valley. Higher up the Little Miami, Mill Creek, and the Miami the streams have cut less deeply and are flowing nearer the terrace level. In most places near the northern edge of the county the streams are flowing on top of the deposits which farther down the valleys constitute the terraces. The higher terraces, where exposed, seem to be composed mainly of gravel and sand down to stream level, but borings are too few to indicate the character of the deposits below that level. One of the characteristic features of the terrace gravels is the occurrence in them of layers, locally called cement rock, which have been cemented into a hard crust by the deposition of iron oxide by percolating waters. The lower terraces, however, consist of the same succession of sands, clays, buried soils, trees, etc., that is found in the flood plains, the average section in the vicinity of Cincinnati being as follows:[1]

Generalized section of terrace deposits near Cincinnati.

	Feet.
Soil	2–5
Gravel and sand, with seams of loam	40–60
Brick clay, with sand and loam	20–30
Buried soil, trees, leaves, etc	5–10
Gravel and clay	5–10
	72–115

[1] Orton, Edward, Geol. Survey Ohio, vol. 1, 1873, p. 432.

Here and there small amounts of water accumulate in irregularities of the surface of the cemented layers in the gravelly portions of the high terraces, and some water is found in clay layers in the low terraces along the Ohio. To procure satisfactory supplies, however, wells must be carried to the general water level, which is commonly about at the elevation of the adjacent streams. As in the alluvial deposits, the terrace waters from the clays are high in phosphate of iron. The waters from the underlying gravels are likewise in all respects similar to those described under the alluvium.

LOESS.

Capping the flat uplands and certain of the high terraces is a thin mantle of a yellowish, somewhat clayey silt, known as loess. The deposits are best developed near the river, where they may have a thickness of 5 to 10 feet or more. From the river bluffs the thickness declines somewhat rapidly to the north, the deposits being of little importance except within a few miles of the Ohio. The loess, because of its thickness, is of no consequence as a water-bearing formation, but it assists materially in absorbing and holding rain water and in feeding it to the underlying till or weathered rock.

TILL.

Except on the steep bluffs facing the streams, Hamilton County is covered by a thin mantle of pebbly clay or till, ranging in thickness from 5 to 25 feet and in color from yellowish in the upper 5 or 10 feet to blue in the lower part. Much of the till is somewhat gravelly and some of it may even include beds of water-deposited sand or gravel.

The till affords supplies to shallow wells at many places on the upland plateaus, especially where it is 15 feet or more in thickness. Where it is thinner it is chiefly of importance in collecting the rain water and feeding it to the underlying rocks. Where gravelly layers are found on the flat uplands good supplies are procured, but near the edge of the bluffs, where the water may escape readily, they are more difficult to obtain.

MORAINAL DEPOSITS.

Morainal deposits are very sparingly developed in Hamilton County, being confined to a very small area near the point where Mill Creek enters the county. They consist largely of gravels and sands, but include some clay or till. They form knolls and small hills from 10 to 20 feet or more in height and constitute a part of

the general belt which enters the county from the northeast near Sharonville and turns northwestward at Mill Creek, skirting the northern boundary on one side or the other as far as the Indiana line. Owing to the predominance of porous gravels water is rarely retained in the morainal deposits and wells in general must penetrate the underlying formations to procure adequate supplies. Where till predominates in the moraines the water supply is the same as in the sheet of pebbly till.

ROCK FORMATIONS.

RICHMOND AND MAYSVILLE FORMATIONS.

The Richmond and Maysville formations compose the upland surface throughout Hamilton County and occupy the upper parts of the bluffs down to about 300 feet above the Ohio. The surface of the rocks is generally much weathered and more or less disintegrated to a depth of several feet. The beds exposed appear to be between 400 and 500 feet in total thickness and to consist mainly of alternating layers of limestone and shale 1 to 10 inches thick; in some places, however, as near the junction between the two formations, shale beds predominate.

Owing to the presence of the loess and till considerable quantities of rain water are collected and fed to the disintegrated upper portion of the Richmond and Maysville formation. Open wells penetrating to this weathered surface usually get sufficient water for ordinary domestic and farm purposes, but drilled wells rarely procure adequate supplies.

EDEN SHALE.

The Eden consists of gray or bluish shales weathering olive or brownish and having a thickness of about 250 feet. Except for a few thin seams of limestone, it contains no porous or soluble layers in which water can circulate. The formation occupies the lower 250 feet of the bluffs, extending up the larger valleys to points beyond the county line. Its base is a little below the level of the Ohio flood plain.

The Eden shale affords no water whatever to drilled wells and in few places yields enough to supply even ordinary dug wells.

UTICA SHALE.

The Utica shale consists of a few feet of shale immediately underlying the Eden, which it closely resembles in character. It is likewise not water bearing.

POINT PLEASANT FORMATION.

The Point Pleasant formation consists of hard, compact, dark shale in layers up to 10 inches or more in thickness, alternating with similar layers of gray limestone. The total thickness is about 150 feet, of which not more than 50 feet is above river level. The formation shows below the flood-plain level of the Ohio at numerous points throughout the county.

Although this formation carries considerable water locally, the procuring of supplies is very uncertain and the water when found is likely to be salty or sulphurous.

"BIRDSEYE" LIMESTONE.

The "Birdseye" is a massive compact grayish limestone the top of which is about 100 feet below the level of the Ohio. Wells penetrating it obtain more or less water, which, however, is commonly salty. Fresh water is not to be expected.

ST. PETER SANDSTONE.

The St. Peter sandstone is a porous sandstone approximately 400 feet thick, the top of which lies about 700 feet below river level. Wells penetrating the formation get abundant supplies of sulphosaline water, which will rise about 175 feet above the low water of the Ohio, but which, unfortunately, is unfit for anything but cooling purposes.

CAMBRIAN AND ORDOVICIAN DOLOMITE.

The Cambrian and Ordovician dolomite is a varicolored dolomitic limestone or marble, 3,000 feet or more in thickness, lying below the St. Peter. It has been penetrated at Cincinnati to a depth of nearly 1,000 feet without yielding any material supply of water.

CAMBRIAN SANDSTONE.

The Cambrian sandstone, which is a prominent water-bearing formation in other parts of the country, may possibly occur beneath Hamilton County, but its depth, which is at least 4,000 feet below river level, is so great as to make drilling unprofitable, especially as the water it carries is almost sure to be sulphurous and unfit for use.

NOTES BY TOWNS.[1]

ARLINGTON HEIGHTS.[2]

Within a short distance from the surface, wells at Arlington Heights enter blue clay, which is said to be at least 100 feet thick. Driving is very difficult and drilling or jetting is sometimes done. A layer of old wood, tree bark, etc., is reported at about 100 feet.

[1] The notes on Carthage, College Hill, Elmwood, Harrison, New Burlington, and St. Bernard are by Frederick G. Clapp.

[2] Conditions in 1906.

CALIFORNIA.[1]

Eight test borings, extending in a northeast-southwest direction from the New Richmond pike at California to a point in the river near the Kentucky shore, were sunk in 1896 and 1897 by the board of trustees, commissioners of waterworks of Cincinnati. They brought out the interesting fact that the rock bottom of the Ohio is only about 50 feet below low-water mark. Sections of borings on the river bank and in the river bottom are given below:[2]

Section of boring on terrace at California.

[Elevation 59 feet above low water.]

	Ft.	in.
Yellow clay	28	
Clay and fine sand	3	1
Gravel and sand	8	8
Coarse sand	25	8
Sand and gravel	1	4
Coarse sand	8	3
Small gravel, sand, and large bowlders	1	6
Coarse sand and gravel	12	6
Coarse gravel	10	8
Bedrock	6	2
	105	10

Section of boring in river bed at California.

[Elevation of river bed 9 feet 2 inches below low water.]

	Ft.	in.
Coarse sand	4	
Fine gravel	4	8
Medium sand	8	9
Fine gravel	14	
Bedrock		10
	32	3

A 90-foot well, 4 inches in diameter, located on the river bank, fluctuates with the river. Where the rise is only 3 to 5 feet the well responds in a few hours, but with a rise of 50 feet the lag may be three or four days. During a small rise the well water stands 2 feet lower than the river, but during a large rise it is as much as 18 feet lower. The slowness of the response indicates the lack of free connection between the waters of the river and those of the alluvium, although the latter, as shown by the record, is nearly pure sand and gravel at this point. In the absence of analyses it can not be determined whether the rise in the well is due to the ponding of the ground water or to the penetration of waters from the river into the alluvium.

[1] Conditions in 1906.

[2] Second Ann. Rept. Board Trustees Com. Waterworks of Cincinnati, Jan. 1, 1899, following p. 70.

CARTHAGE.[1]

The waterworks of Carthage are situated on the valley bottom at the western edge of the village, close to the Miami & Erie Canal, below the base of the surrounding hills. The supply is obtained from four 6-inch driven wells, two 135 and two 137 feet deep. The water is found in gravel and is pumped by direct pressure into an 80,000-gallon cistern on the level of the pumping station and thence into the water mains. The pumps are run day and night. This water system was constructed in the year 1890, being the first plant in southern Ohio built and operated by an incorporated village. The same system supplies the towns of Elmwood and Winton Place and several factories.

In and near the village of Carthage there are a number of drilled wells. One of them, belonging to the Chatfield Manufacturing Co., on the corner of Fifth and Lebanon streets, is about 200 feet deep. The principal water supply was obtained at 60 feet in gravel, and bedrock was struck at 100 feet. The ordinary water level is 40 feet below the surface. The temperature is 55° to 60°, and 50 to 60 gallons of water a minute can be obtained.

On the slope of the hills directly east of Carthage is situated the Longview Hospital, which has an excellent supply of water from three drilled wells, 143, 146, and 150 feet deep. The wells are 8 and 10 inches in diameter and are sunk entirely in gravel, no rock being penetrated. They lie in line with the abandoned gravel-filled valley extending southeastward from the Miami to the Ohio. The principal water vein was struck at about 50 feet from the surface. The water is used for all domestic purposes and for boilers to supply 1,350 inmates. The pumps are run nine hours a day, pumping about 250,000 gallons of water from the station near the base of the slope to a reservoir on the hill. A mechanical filter is used. The water is good. For 25 years previous to the installation of the present supply a dug well 40 feet deep was used, but the water finally gave out. Another well was drilled to a depth of several hundred feet, but no data regarding it could be obtained.

CINCINNATI.[1]

General conditions.—Most of the business part of Cincinnati is situated on a gravel terrace standing 500 to 540 feet above sea level or 70 to 110 feet above low-water level of the Ohio, but the portions near the Ohio and bordering Mill Creek are 20 to 40 feet lower and are sometimes partly covered by water during floods. In the outskirts of the city and its suburbs the hills rise to heights of over 900 feet, or 300 feet above the terrace.

[1] Conditions in 1906.

As a consequence of the peculiar situation of the city, great variability in the underground-water conditions has always prevailed. Originally water was obtained by shallow wells, but as the houses became more crowded the water became polluted, making it necessary to go deeper for supplies. For a time moderately deep wells were entirely successful, but as manufacturing establishments multiplied the demand became too heavy for the supply or the water became polluted, so that many of these wells also had to be abandoned, although some are still used. Next, recourse was had to deep drilled wells, many of which were carried to 1,000 feet and some to more than 2,000 feet, but without finding any further fresh water of consequence, although plenty of the sulphosaline water was obtained. At present a few of the dug wells remain on the outskirts of the city and a number of the deep drilled wells are still in use, but most of the well water is obtained from the driven wells sunk in the alluvial or terrace deposits or for a few feet into the underlying rocks. The greater part of the business firms and practically all the citizens use the public supply.

Well records.—An unusually large number of wells have been sunk in Cincinnati owing to the large number of breweries and distilleries, the poor quality of the public supply, and other minor causes. As a result the possibilities of getting water in this way have been pretty well demonstrated. The probable amount of the water in both the unconsolidated deposits and the rock formations has already been discussed and numerous supplementary data are given in the tables (pp. 122–123, 130, 202–203). It only remains to present a few additional facts as to the nature of the materials and the position of the bedrock surface. The character of the deposits is best shown by the following log, which represents the best available record in the vicinity. The correlation of geologic formations is added by the writer.

Record of well of Cincinnati Gas Co., Front Street.[a]

	Thickness.	Depth.
	Feet.	*Feet.*
Artificial filling	5	5
Soil	5	10
Alluvium:		
Blue clay	20	30
Sand and gravel	90	120
Point Pleasant formation:		
Shale	3	123
Blue limestone	40	163
Blue and gray limestone	50	213
Sandstone	5	218
"Birdseye" limestone:		
Limestone	380	598
White limestone	240	838
St. Peter sandstone:		
Sandstone	65	903
Sandstone, very hard	15	918
Red sandstone	62	980
White sandstone	85	1,065
Coarse sandstone and limestone	15	1,080
Sandstone	140	1,220
Cambrian and Ordovician dolomite: Very hard red and white marble	25	1,245

[a] Bell, T. J., History of the water supply of the world, Cincinnati, 1882, pp. 1–7.

Of the shallower wells that of Timothy Kirby at Cumminsville is of interest as showing the succession of materials in the Mill Creek valley.

Record of Kirby well, Cumminsville.[a]

	Thickness.	Depth.
	Feet.	*Feet.*
Soil and brick clay	12	12
Sand	4	16
Blue clay with gravel	34	50
Gravel	19	69
Coarse sand	3	72
Sand with coaly fragments	11	83
Blue clay with gravel (base level with low water of Ohio)	9	92
Blue clay, sand, and coaly fragments	16	108
Sand, gravel, blue clay, and coaly fragments	43	151

[a] Geol. Survey Ohio, vol. 1, p. 433.

The well of John Kaufman on Vine Street illustrates the character of the terrace materials in that part of Cincinnati. The distance to rock is among the greatest recorded at Cincinnati.

Record of Kaufman well, Vine Street.

	Thickness.	Depth.
	Feet.	*Feet.*
Blue clay	25	25
Sand and quicksand	75	100
Blue clay	55	155
Quicksand and gravel	35	190
Limestone	25	215

The borings made by the board of trustees bring out the character of the deposits in the narrow part of the Ohio Valley opposite Dayton, Ky.:

Record of boring in river between Torrence Road, Cincinnati, and Dayton, Ky.

[Starts 5 feet above low-water mark.]

	Thickness.	Depth.
	Ft. in.	*Ft. in.*
Coarse gravel and bowlders	11 8	11 8
Sand	2	13 8
Coarse gravel and bowlders	12 4	26
Fine sand	13 2	39 2
Limestone	4 11	44 1

Record of boring at foot of Lumber Street, Cincinnati, opposite Dayton, Ky.

[Starts 54 feet 10 inches above low-water mark.]

	Thickness.	Depth.
	Ft. in.	*Ft. in.*
Sand and bowlders	3	3
Blue clay	3 4	6 4
Brown and black clay	29 2	35 6
Gravel	4 10	40 4
Blue clay	7	40 11
Clay and soapstone	3 6	44 5

The borings represented by the next three records show the character of the materials along a section extending from East Cincinnati to California, across the valley of the Little Miami. The first is located about half a mile south of Columbia, the second on the west bank of the Little Miami, and the third on the terrace near California on which the filter beds are located.

Record of boring near junction of Turkey Bottom Road and Richmond Pike.

[Starts 59 feet 7 inches above low-water mark.]

	Thickness.		Depth.	
	Ft.	*in.*	*Ft.*	*in.*
Loam	10		10	
Sandy loam	12		22	
Blue clay	13	1	35	1
Gravel	23	1	58	2
Brown sand	27	4	85	6
Gray sand	7	2	92	8
Gravel	6	11	99	7
Rock		10	100	5

Record of boring on west bank of Little Miami three-fourths of a mile above the mouth.

[Starts 40 feet 6 inches above low-water mark.]

	Thickness.		Depth.	
	Ft.	*in.*	*Ft.*	*in.*
Clay	24	10	24	10
Gravel	9	7	34	5
Coarse sand	5	8	40	1
Fine sand	30		70	1
Gravel	5	6	75	7
Yellow and blue clay	1	2	76	9
Rock		7	77	4

Record of boring on site of filter beds, California, Ohio.

[Starts 98 feet 10 inches above low-water mark.]

	Thickness.		Depth.	
	Ft.	*in.*	*Ft.*	*in.*
Sandy loam	10		10	
Yellow clay	3		13	
Fine sand	33		46	
Blue clay	49		95	
Gray sand	15		110	
Brown sand	9		119	
Black sand	2		121	
Sand, gravel	10	4	131	4
Bedrock		2	131	6

Rock floor.—A study of the well records brings out a number of interesting facts regarding the configuration of the rock surface beneath Cincinnati and the old channel. Near the bluff which borders the city on the northeast the rock is relatively high, generally being

within 40 or 50 feet of the surface, or nearly 50 feet above low water in the Ohio. A quarter of a mile from the foot of the hills, however, the rock is between 50 and 75 feet from the surface, or only 20 feet above low-water mark, and a little farther out it drops abruptly to about 150 feet, or 50 feet or more below low water. These depths occur along a line extending from a point west of the suspension bridge northward and northwestward to the corner of John and Liberty streets, beyond which the depth to rock is not known. Rock is penetrated by wells between the Chesapeake & Ohio and suspension bridges, at the Gibson House, Emery Hotel, Palace Hotel, and near the corners of Elm and Canal streets, Dayton Street and Central Avenue, and Liberty and John streets. To the east, as shown by wells in the vicinity of Ludlow Street, rock is well above river level, coming within 30 or 40 feet of the surface. Similar depths are shown by wells near the Cincinnati, Hamilton & Dayton depot and near the corner of Front and Harriet streets. These depths indicate a deep channel running at right angles to the Ohio and connecting with an old channel of Licking River near the Chesapeake & Ohio Railway bridge, representing without doubt the course of the Licking when it flowed northward to join the old Ohio—then flowing in the vicinity of Norwood back of Cincinnati (p. 19) and north of St. Bernard.

The depth to rock in the Mill Creek valley south of the Liberty Street viaduct is not so great as it is in the old Licking channel, though greater than under the land immediately to the east and somewhat more than in the present Ohio channel above the mouth of the Licking, where the rock appears to be at no great distance below the bottom.

Deep wells.—A large number of wells have been drilled in Cincinnati and vicinity, particulars of a considerable number of which are given in the following table. Many of them were sunk years ago, and most of the data have long been lost; others were put down by drillers who have since died or moved to other localities; and still others were sunk by drillers who kept no memoranda. The information presented affords, however, an indication of the thickness of the surface deposits, the depth to the rock floor, and the character and volume of water supplies.

Data on wells at Cincinnati.

Owner.	Location.	Driller.	Diameter.	Depth.	Depth to rock.	Head.	Temperature.	Yield.	Beds penetrated.
			Inches.	*Feet.*	*Feet.*	*Feet.*	*°F.*	*Gallons per minute.*	
American Oak Leather Co.		—— Koehne	8	180	100	−100		200	Point Pleasant.
Bank & Safe Co	Front Street opposite Rose Street.	Ed. Boluss		90	90			Plenty	Alluvium.
Banner Brewery Co	Canal and Walnut streets	John Pepper		800	60			Abandoned	"Birdseye," top St. Peter.
Banner Ice Co		A. D. Cook	10	80	80	− 53			Alluvium.
Broadway Electric Plant	Broadway, above Court Street.	Bradford Well Co		1,200				Abandoned	St. Peter.
Christian Moerlein Brewing Co.	2000 Elm Street	Christian Moerlein Brewing Co.	8	90		− 81		2½ inch stream	Alluvium.
Cincinnati Gas Co	Front Street, between Rose Street and Gas Alley.	Ed. Boluss		1,125	125				St. Peter.
Do	West Front Street		4½	1,360		82	60	138	Do.
Do	Eastern Avenue		6	1,475		104	61	500	Do.
Cincinnati, Hamilton & Dayton depot.	Sixth Avenue	John Pepper		250	35			No water; a little gas	"Birdseye."
Cincinnati Ice Co			6	265–300		− 0			Do.
Clifton Springs Distilling Co.	Ludlow Avenue, Twenty-third ward.	J. J. Groves	8	1,960	50	+ 0	63	158	St. Peter.
Coast & Coast	Spring Grove Avenue	William Hendrigsman.	4	85	85	− 60			Alluvium.
Consumers' Ice Co		E. Hendrigsman	8	405	35				"Birdseye."
Crystal Springs Ice Co	Cumminsville	—— Hendrigsman	6	120	120	− 25	56	35	Alluvium.
Tom E. & N. Davis	Cincinnati, Hamilton & Dayton Railway and Gest Street.	Ed. Boluss		60	60			Plenty	Do.
Diamond D. Co	Gest Street and Mill Creek	do		68	68			do	Do.
Frank Douglas	Monroe Street (Straker Swamps).	H. Pegg		250	132			Good water at intervals of about 15 feet.	Point Pleasant, "Birdseye."
Eggerr Sanger Planing Mill	Foot of Harriet Street	Ed. Boluss		150	35			No water	Point Pleasant.
Emery Hotel	Vine Street, between Fourth and Fifth streets.	do	3	148	148			Hard water; iron.	Alluvium.
Foss-Schneider Brewing Co.		A. D. Cook	6	85	No rock.	− 55			Do.
Freiberg & Workum	Sycamore and Main streets	Ed. Boluss		240	48			Little gas	Point Pleasant, "Birdseye."
Gaff Distilling Co	Sixth Street and Mill Creek	John Pepper		1,265	110				St. Peter.
Gambrino Stock Co	Sycamore Street	Ed. Boluss		60	60			Little water	Alluvium.
A. Gander Packing Co		—— Cook	8	80	80	− 33			Do.
Gerkie Brewery Co	Plum and Canal streets	John Pepper		160	160				Do.
Gibson House				370	146				Point Pleasant, "Birdseye."
Do	Walnut Street, between Fourth and Fifth streets.	Ed. Boluss		564	168				Do.
Globe Rolling Mill	Front and Smith streets	J. E. Yingling		110	110				Point Pleasant.
Globe Soap Works	Water and Walnut streets	—— Cook		70	70			Little water; abandoned.	Alluvium.

Hall Safe & Lock Co.	Pearl and Plum streets	Ed. Boluss		110	110			Plenty	Do.
J. Hanck	Corner Dayton Street and C Avenue.	do		170	150				Point Pleasant.
James Heakin Spice Co.	Front Street, between Walnut and Vine streets.	do		90	90			Lots of it	Alluvium.
Holders Tannery	Colerain Pike		4	215					Point Pleasant.
—— Hulsman	John Street, near Liberty		4	161	161				Alluvium.
Hygeia Ice Plant	Court Street	Bradford Well Co		500	70			No water	"Birdseye."
W. W. Johnson	Sycamore and Yeatman streets.		3	80	80				Alluvium.
Jung Brewery Co		Ed. Hendrigsman	8	165	165	−100			Do.
Kauffman Brewing Co	Vine Street, between Liberty and Green streets.	Ed. Boluss		140					Do.
John Kaufman	Vine Street		4	215					Point Pleasant.
Keck's Fertilizing Works	Cumminsville			1,380			60		St. Peter.
Herman Lackman	Sixth Street	John Pepper		60	60				Alluvium.
Liberty Street viaduct				145	142				Point Pleasant.
Longview Hospital		J. D. Cook	8	143 146		− 45	50	500	Alluvium.
		Bradford Well Co	10	150	Norock.	− 50			
Mayflower House	Gest Street and Mill Creek	Joe Sands		60	60			Plenty	Do.
Meier Furniture Factory	Front Street, between Rose and John streets.	Ed. Boluss		90	90			do	Do.
Mill Creek Distillery	West of Mill Creek		4½	1,440		+ 90		267	St. Peter.
Moerlein Brewing Co	North Elm Street		4	2,408			62	400	Do.
Mosler Safe & Lock Co	Elm Street, between Pearl and Second streets.	Ed. Boluss		110	110			Plenty	Alluvium.
National Lead Co	Seventh and Freeman streets.	do		60	60			Small quantity	Do.
Ohio & Kentucky Kid Leather Co.		Bradford Well Co		265	60	− 25		25	Point Pleasant, "Birdseye."
Ohio Butterine Co	Walnut and Second streets	Ed. Boluss		68	68			Lots of it	Alluvium.
Palace Hotel	Sixth and Vine streets	J. E. Yingling		140	140			Too little	Do.
Pugh Printing Co	Lawrence Street, between Fourth and Fifth streets.	Ed. Boluss		200	40			No water	Point Pleasant.
Rabes Distillery	Cumminsville		4½	1,400		+ 70		100	St. Peter.
J. C. Roth Packing Co		A. D. Cook	8	85	85	− 65			Alluvium.
Russell Morgan Printing Co	Lock Street and Eggleston Avenue.	Ed. Boluss		300	25			No water	Point Pleasant, "Birdseye."
Schaller Brewery Co	McMicken Street	do		600				do	Do.
Jacob Schlachter		—— Cook	6	80	80	± 60	56		Alluvium.
J. Schlachter & Son, Packers	2833 Colerain Avenue		6	90		− 74	56		Do.
Schmals Brewery Co	McMicken Street	John Pepper		400–500				No water	Point Pleasant, "Birdseye."
Schmidlapp & Senior Clifton Springs Distilling Co.		Hutchinson Construction Co.	10	160	40	− 0			Point Pleasant.
Do		—— Rose	8	1,750	100	+ 0			St. Peter.
J. & F. Schroth Packing Co		—— Isenbr	6	150		− 0			Alluvium.
Walker Brewing Co	Sycamore Street	Ed. Boluss		140	60				Do.
Windisch Muhlhausen Brewing Co.		Bradford Well Co	6	170	160	−70 to −90			Point Pleasant.
Do	Canal		4	180	180				Alluvium.

Public supplies.[1]—The public supply of Cincinnati has for many years been obtained from Ohio River, the water being used without treatment. The water is nearly always muddy and is at all times more or less polluted by sewage from cities farther up the stream, giving rise to numerous cases of typhoid fever and other filth diseases. Of late years, owing to accidents to the machinery and other causes, the supply has often been entirely inadequate, the upper part of the town being practically without water for days at a time. The urgent need of new supplies was finally recognized and steps taken to investigate the available sources.

The great advantages of well water over river water in palatability and in safety were apparent. The possible sources of supply suggested were rock wells and alluvium wells or infiltration galleries. It was quickly concluded, however, that none of these sources was practicable. Cincinnati is, in fact, very poorly located for obtaining supplies from underground sources. As it is underlain by limestones and shales extending to a depth of 900 feet or more and carrying water only in smallest amounts—insufficient even for private wells—a public supply from these formations is out of the question. Below the limestone lies the St. Peter sandstone, which, as has been shown by the success of many of the deep brewery wells, yields larger supplies. The head of the water, however, has already been lowered and the supply decreased by the relatively few private wells drawing upon it, making it clear that the supply would be insufficient for the city's needs, even if the water were suitable. This, however, is not the case, the water being exceedingly hard and highly charged with salt, iron, and sulphur, which gives it a very strong and objectionable taste. Moreover, some of the constituents would actively attack boilers and pipes and greatly shorten their lives. As there is no known method of treating such waters economically, their use is out of the question.

The alluvium, although present over considerable areas along Ohio and Little Miami rivers and yielding enough water for many industrial establishments, does not afford at any point sufficient supply to warrant the belief that enough for the city's use could be obtained from a single or even from several localities. To obtain the desired amount, in fact, it would be necessary to construct a considerable number of scattered and entirely separate pumping plants, the cost of operating which would be prohibitive. Besides, the waters of the ordinary alluvium are very hard, containing several times the amount of incrusting constituents carried by the river water. This is brought out in the following summary:

[1] Conditions in 1906.

Comparative composition of water from alluvium and river water.

[Parts per million.]

Source.	Chlorine.	Incrustants.		Total solids.
		Sulphates.	Carbonates.	
Alluvium (average of 50 samples)	18	95	331	350
River (daily analyses 1898)	10	33	45	120

A source of supply that has been successful at other localities is a series of infiltration wells or galleries sunk in sand bars in the river or along the river banks. Where the demands are relatively small this method works admirably, but it is open to several objections for a large city like Cincinnati. One of the strongest of these is the liability of the uncovering of the wells or galleries by changes in the bottom of the stream or in its banks in times of flood, leading either to the destruction of the entire plant or, at least, to the removal of filtering materials and an influx of raw water. Moreover, between floods, silts are likely to collect over the infiltrating surfaces, resulting in a clogging of the pores. Again, though this method would yield more water than would wells in ordinary alluvium, it is almost certain that several plants would have to be maintained in order to procure the necessary amounts. The supplies under this system can not be so readily increased under new demands as can those directly from the river. Forced pumping would be dangerous for the reason that the water would be drawn through with insufficient filtration.

On the whole it seems certain that the obtaining of supplies for the city of Cincinnati from underground sources is out of the question, or, at least, would be more costly than filtered river water, which it was finally decided to introduce. If the plant is efficiently managed the filtered water should be safe for domestic use and it has the advantage of being much softer and more suitable for boilers than waters from underground sources.

COLLEGE HILL.[1]

The village of College Hill lies on the uplands, where the glacial drift averages about 15 feet in depth. The water supply is purchased from the city of Cincinnati, but there are a few dug wells in the village that range from 18 to 35 feet deep and one drilled well that extends to a depth of 201 feet. The wells are reported to yield a fair amount of water, but that from the dug wells is not recommended for drinking. The water of the public supply at College Hill is reported to be of much better quality than the same water in

[1] Conditions in 1906.

Cincinnati, for the reason that it is pumped from the Mount Auburn Reservoir to the standpipe at College Hill, and in both of these places it has a chance to settle.

ELMWOOD.[1]

At the western edge of Elmwood the works of the Laidlaw-Dunn-Gordon Co. are supplied by eight drilled wells 8 inches in diameter, which seem to give satisfaction. The record of one of them is as follows:

Record of deep well of Laidlaw-Dunn-Gordon Co., Elmwood.

	Thickness.	Depth.
	Ft. in.	*Ft. in.*
Earth	4 0	4 0
Sand and gravel	6 0	10 0
Fine sand	6	10 6
Blue clay	57 6	68 0
Bowlders	3 0	71 0
Water-bearing sand. Very rough bowlders.	41 0	112 0

The water in three wells stands 4 feet from the surface; and 280 gallons a minute can be obtained from a single well for an hour at a time, one well being pumped by an air lift, the rest by steam head.

HARRISON.[1]

The town of Harrison is supplied with water by the Harrison Water & Light Co., which owns four driven wells on the flood plain of Whitewater River, situated 200 feet from the river, a short distance west of Harrison, in Indiana. From the wells the water is pumped to a standpipe 110 feet in height. The wells are about 40 feet in depth and are entirely in river gravel.

IVORYDALE.[1]

At Ivorydale, about one-fourth mile west of the waterworks at St. Bernard, on the flood plain of Mill Creek, are the works of the Procter & Gamble Co., which are supplied by eight wells sunk in gravel and four wells drilled into rock. The rock wells are 1,200 to 1,600 feet in depth, and obtain very salty but very cold water, which is used for condensing. The gravel wells are only 117 to 150 feet deep and struck rock at 117 to 120 feet. They are 8 to 10 inches in diameter. It is reported that 3,000,000 gallons a day are pumped from the eight wells by an air compressor. The water is used for drinking, for condensing, and, after being treated, for boilers. When not pumped it stands 20 to 25 feet below the surface.

[1] Conditions in 1906.

The following record of a well at the Procter & Gamble works is of interest as showing the large preponderance of "clay" in the deposits of Mill Creek at this point, the proportion being much greater than at Connorville, a short distance farther down the valley. It is quite possible that a considerable part of the clay is in reality a clayey till. The well is located 74 feet above low water of the Ohio.

Record of well of Procter & Gamble, Ivorydale.[a]

	Thickness.	Depth.
	Ft. in.	*Ft. in.*
Loam	5 8	5 8
Gravel	5 0	10 8
Clay	49 4	60 0
Sand and gravel	5 0	65 0
Yellow sand	11 6	76 6
Clay	20 6	97 0
Gravel and sand	1 0	98 0

[a] James, J. F., Proc. Cincinnati Soc. Nat. Hist., vol. 11, 1888, pp. 102–103.

Two other wells were drilled at this place, but in them the gravel was cut out by clay and the water vein was not struck.

MADISONVILLE.[1]

The public supply of Madisonville is obtained from three 140-foot wells sunk in the deep gravel and sand deposits filling the old Ohio River channel (p. 20). Plenty of water is obtained, a large proportion of the inhabitants of the town availing themselves of the public supply. Very few private wells are to be found. Further tem will be found in the table on page 52.

NORWOOD.[1]

Norwood, like Madisonville, is located on the gravels occupying the old channel of the Ohio and has very few private wells, most of the people depending on the public supply. A number of the manufacturing establishments, however, have wells, some of which are of considerable depth and yield large supplies.

The deepest well in town is said to be that of the United States Playing Card Co., which has a diameter of 10 inches and a depth of 400 feet, all but 148 feet of which is reported to be in rock. This well will yield with an air lift 425 gallons a minute without lowering the supply.

[1] Conditions in 1906.

Another well sunk in 1906 struck rock at 220 feet. The record of this well, by 20-foot intervals, is as follows:

Record of deep well, Norwood, Ohio.

	Feet.
Soil and coarse sand	20
Blue clay	40
Gravel and rock	60
Fine gravel	80
Blue clay	100
Blue clay and gravel	120
Sand	140
Coarse sand with pebbles	160
Water sand	180
Gravel	200
Blue clay or shale	220
Rock	240

The record is of interest in showing a considerable amount of blue clay, a part of which is probably till. A generalized section of the deposits at Norwood is given by a local driller as follows:

Generalized section of wells at Norwood, Ohio.

	Thickness.	Depth.
	Feet.	*Feet.*
Clayey sand and gravel	100	100
Water-bearing gravel	15	115
Hard shaly clay	15	130
Fine sand	35	165
Gravel and cobbles	60	225
Rock.		

Norwood has a public supply derived from two deep wells sunk in materials similar to those of the section given in the preceding paragraph. The water is of good quality and is abundant, supplying both Norwood and the village of Idlewild. Particulars of the system will be found in the table on page 52.

ST. BERNARD.[1]

The public supply of St. Bernard is drawn from two 15-inch drilled wells, sunk on the inner edge of the flood plain of Mill Creek at the base of the surrounding hills. The water is raised by an air lift and is pumped by direct pressure to a 270,000-gallon standpipe 125 feet above the main street. Five wells were originally drilled, to depths of 105 to 270 feet, but the casing of three of them gave

[1] Conditions in 1906.

out and they were abandoned. One of the wells still in use obtains 90 gallons of water a minute with a steam-head pump. The second well is pumped by an air lift, by which a maximum yield of 550 gallons a minute can be obtained. The water stands 41 feet from the surface and is lowered 7 feet when pumped for three to five hours. Although the water is obtained in gravel at a depth of 132 to 135 feet, one of the wells is 270 feet deep, having struck rock at 135 feet. The waterworks wells are reported to have robbed all the shallow wells within a mile. Some of the shallow wells went to depths of 30 to 60 feet. The water in dug wells here is not so hard as that in the wells of the public supply.

SYMMES TOWNSHIP.[1]

Chappendocia Springs, located in Symmes Township, in a ravine on the west side of Little Miami River, about 2 miles below Loveland, emerge from a yellow clay resulting from the weathering of the underlying limestone and shale. The water, which is chalybeate in character, was formerly extensively distributed in Cincinnati but is not at present sold, although it may be put on the market again in the near future.

WYOMING.[1]

The waterworks of Wyoming, situated on the west side of the Cincinnati, Hamilton & Dayton Railway, near the north end of town, comprise four 8-inch driven wells in the valley gravels. One well is 104 feet deep and the other three 197 feet deep. The latter pass through 8 feet of gravel and strike bedrock at the bottom. The water in all of them occurs in gravel and rises within 45 feet of the surface. An air compressor is used and 450 gallons of water a minute can be obtained. At least 1,000,000 gallons of water is reported to have been pumped in 24 hours. By pumping 1,400 gallons a minute from three of the wells for 24 hours, the water in the other well is lowered 5 feet. These waterworks supply not only Wyoming, but also the villages of Hartwell, Lockland, and Arlington. The water is pumped into a reservoir 234 feet above the pumping station, the capacity being 4,000,000 gallons. The system was installed in 1892.

WATER PROSPECTS.

A summary of the underground water conditions in Hamilton County is presented in the following table:

[1] Conditions in 1906.

Underground-water conditions in Hamilton County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Addyson	Terrace gravel.		Plenty	Eden, Point Pleasant.	Point Pleasant	Small.
Andersons Ferry	do	100±	do	do	do	Do.
Asbury	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Avondale	do			do	do	Do.
Bevis	do	15		do	do	Do.
Blue Ash	do	15	Moderate	do	do	Do.
Bond Hill	Gravel, glacial.	Deep.		Point Pleasant	Point Pleasant	Do.
Brecon	Till	60+	Fair	Richmond and Maysville.	Richmond and Maysville.	Do.
Bridgetown	do	15		do	do	Do.
California	Alluvium			Point Pleasant	Point Pleasant	Do.
Camp Dennison	do	100+	Plenty	Eden	do	Do.
Carthage	Alluvium, glacial gravel.	250±	do	Point Pleasant	do	Do.
Cedar Point	Till	15	Moderate	Richmond and Maysville.	Richmond and Maysville.	Do.
Cherry Grove	do	10	Plenty	do	do	Do.
Cheviot	do	15	Moderate	do	do	Do.
Cincinnati	Alluvium, till, terrace gravel.	5–150	do	Eden, Point Pleasant.	Point Pleasant (see also notes).	Do.
Cleves	Alluvium		Plenty	Point Pleasant	Point Pleasant	Do.
Cluff	do			Eden	do	Do.
College Hill	Till	15	Small	Richmond and Maysville.	Richmond and Maysville.	Do.
Creedville	do	15	do	do	do	Do.
Crescentville	Drift			Eden	Point Pleasant	Do.
Delhi	Terrace sands	100+	Plenty	Eden, Point Pleasant.	do	Do.
Dent	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Dunlop	do	15		do	do	Do.
Eightmile	Alluvium, talus.			Eden	Point Pleasant	Do.
Elizabethtown	Alluvium	50	Moderate	Point Pleasant	do	Do.
Elmwood	do	Deep.	Plenty	do	do	Do.
Fernbank	do	70	do	do	do	Do.
Forestville	Till	15	Moderate	Richmond and Maysville.	Richmond and Maysville.	Do.
Fruit Hill	do	20	do	do	do	Do.
Glendale	do	200+	Plenty	Eden	Point Pleasant	Do.
Groesbeck	do	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Harrison	Alluvium, glacial gravel.	100+	Plenty	Eden, Point Pleasant.	Point Pleasant	Do.
Hartwell	Alluvium	200±	do	Eden	do	Do.
Hazelwood	Till	20+	do	Richmond and Maysville.	Richmond and Maysville.	Do.
Home City	Terrace sands.	140+	do	Eden, Point Pleasant.	Point Pleasant	Do.
Hyde Park	Till	15	Small	Richmond and Maysville.	Richmond and Maysville.	Do.
Ivorydale	Alluvium	100	Plenty	Point Pleasant	Point Pleasant	Do.
Kennedy	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Lockland	Alluvium	Deep.	Plenty	Eden	Point Pleasant	Do.
Mack	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Maderia	Alluvium	20	Moderate	Eden (?)	Point Pleasant	Do.
Madisonville	Glacial gravel.	150	Plenty	Point Pleasant	do	Do.
Miami	Alluvium	Deep.		Eden	do	Do.
Miamiville	Terrace gravel.	50+	Plenty	do	do	Do.
Monfort	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Montgomery	do	15	Fair	do	do	Do.
Mount Airy	do	15		do	do	Do.
Mount Healthy	do	18	Moderate	do	do	Do.
Mount St. Joseph	do			Eden	Point Pleasant	Do.
Mount Summit	do	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Mount Washington.	Till, old gravels.	20	Plenty	Eden	do	Do.
New Haven	Alluvium		do	Point Pleasant	Point Pleasant	Do.
Newtown	do	Deep.	do	do	do	Do.
North Bend	Terrace gravel.	100±	do	do	do	Do.
Norwood	Glacial gravels	Deep.	do	do	do	Do.

Underground-water conditions in Hamilton County—Continued.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Oakley	Glacial gravels	Deep.	Plenty	Point Pleasant	Point Pleasant	Small.
Plainville	Alluvium	35+	do	Eden	do	Do.
Pleasant Ridge	Till	12	Moderate	Richmond and Maysville.	Richmond and Maysville.	Do.
Pleasant Run	do			Eden (?)	Point Pleasant	Do.
Preston	Alluvium			Point Pleasant (?)	do	Do.
Price Hill	Till	10		Richmond and Maysville.	Richmond and Maysville.	Do.
Reading	Alluvium			Eden	Point Pleasant	Do.
Remington	Terrace gravel.	50+	Plenty	do	do	Do.
Riverside	do	100±	do	Eden, Point Pleasant.	do	Do.
Rossmoyne	Till		Small	Richmond and Maysville.	Richmond and Maysville.	Do.
St. Bernard	Glacial gravels	120	Plenty	Point Pleasant	Point Pleasant	Do.
Sater	Terrace gravel.			Eden	do	Do.
Sedamsville	Alluvium, terrace gravel.	100±	Plenty	Eden, Point Pleasant.	do	Do.
Sekitan	Terrace gravel.	100±	do	do	do	
Sharonville	Till, moraine			Eden	do	Do.
Silverton	Till	20		Richmond and Maysville.	Richmond and Maysville.	Do.
Sixteenmile Stand.	do	30+	Fair	do	do	Do.
Snyder	Alluvium			Eden (?)	Point Pleasant	Do.
Springdale	Till, moraine			Eden	do	Do.
Sweetwine	Alluvium, talus.			Point Pleasant	do	Do.
Symmes	Alluvium	25	Plenty	Eden	do	Do.
Taylors Creek	do			do	do	Do.
Terrace Park	Terrace gravel.	75+	Moderate	do	do	Do.
Transit	Till	15		Richmond and Maysville.	Richmond and Maysville.	Do.
Trautman	Terrace gravel.	100±	Plenty	Eden, Point Pleasant.	Point Pleasant	Do.
Westwood	Till	15	Small	Richmond and Maysville.	Richmond and Maysville.	Do.
Whitewater	Alluvium	Deep.	Moderate	Point Pleasant	Point Pleasant	Do.
Woodlawn	Till	200±	Plenty	Eden	do	Do.
Wyoming	Alluvium	200	do	do	do	Do.

HIGHLAND COUNTY.

By M. L. Fuller.

In Highland County the investigations for the present report were confined mainly to the central and western parts, relatively little attention being paid to the eastern third, which was reserved for future study.

SURFACE FEATURES.

Highland County is characterized by greater diversity of surface than the counties to the north and may be divided into a number of districts according to the nature of its physical features. Along the western border, where the land is lowest, the surface is a flat and to a large extent a marshy drift plain at an elevation of 930 to 1,030 feet, underlain by blue limestone (Richmond). The central part of the county, which is about 100 feet higher, consists of flat-crested, plateau-like ridges alternating with wide, deep valleys, as in the

vicinity of Hillsboro. In the northern part of the county the land is still higher and in general is covered by a smooth mantle of drift, with a few sharp valleys cut in the drift and limestone. At the south boundary the drift is thinner and the land lower and cut by many streams, the average elevation being under 1,000 feet. The highest land in the county is along the eastern boundary, where hills rise to an elevation of over 1,300 feet, or several hundred feet above the adjacent lowlands. The county is crossed in a northwest-southeast direction by two low morainal ridges, one in the northeastern part and the other southwest of Hillsboro.

WATER-BEARING FORMATIONS.

SURFACE DEPOSITS.

ALLUVIUM.

The streams of Highland County are in general of small size, flow in relatively small channels, and are bordered by narrow deposits of alluvium. In the valleys occupied by the gently flowing streams of the flatter portions of the county much of the alluvium is rather fine, sands and silts predominating, but in those of the more swiftly flowing streams, in the more hilly regions the alluvium, if present at all, is commonly in the form of coarse gravel. In some places the streams flow locally on bare rock, no alluvium whatever being present.

The alluvium will usually afford satisfactory supplies to wells, especially in the broader and flatter valleys. In the smaller ravines the gravels are not usually so situated as to be readily available as sources of supply.

TILL.

The pebbly clay or till covers the entire county except the extreme southeast corner, but it is very thin toward its outer edge in the southeast and in many places is difficult to detect. Farther west and north it thickens considerably. In the northwestern half of the county the older drift just described is covered by a younger sheet, which adds materially to the total thickness. The lowest till is usually a blue pebbly clay 20 feet or less in thickness, but in some places yellow, white, or black clays rest on the rock. On top of the blue clay in some localities, especially on the plateaus, is a layer of soil or of more or less peaty deposits, these being in turn covered by 20 or 30 feet of gravelly drift.

The water supplies of the till are not large but are generally abundant enough to supply ordinary wells wherever the till has a thickness of 20 feet or more. Wells encountering the soil zone usually find plenty of water, but it has an objectionable taste and is little used for drinking.

MORAINAL DEPOSITS AND STRATIFIED DRIFT.

Under morainal deposits and stratified drift are included deposits overlying the ordinary till, or pebbly blue clay. In some of the true morainal deposits till forms a considerable part of the materials, but in others the deposits are prevailingly gravelly, with here and there a layer cemented to sandstone or conglomerate by iron or lime. In some places this gravelly material is as much as 90 feet thick. The morainal material reaches its greatest thickness in the belt southwest of Hillsboro and in the northeast corner of the county.

The stratified drift that lies in valleys may carry considerable water, and even on the uplands moderate amounts may be found in the thicker deposits if the land is fairly flat. Where the peaty bed occurs in the till very strong mineral water unfit for use is often obtained.

ROCK FORMATIONS.

CARBONIFEROUS SANDSTONE, OHIO SHALE, AND "HELDERBERG" LIMESTONE.

The Carboniferous (Mississippian) sandstone, 100 feet thick, is the uppermost formation in the county. Just below it lies the Ohio shale (Devonian), 250 feet thick, succeeded by the "Helderberg" limestone (Silurian), 100 feet thick. These formations occupy small areas among the high hills near the eastern border of the county but are outside of the scope of the present investigation, which considers only the "Niagara" and lower rocks.

"NIAGARA" LIMESTONE.

The "Niagara" formation in Highland County has a total thickness of 275 feet and consists, from the base upward, of a few feet of bedded limestone, 60 to 100 feet of shales, 45 feet of yellowish magnesian limestone, 45 feet of blue limestone, 20 to 90 feet of massive magnesian limestone, mainly capping the hilltops, and 30 feet of white to yellow sandstone, known as the Hillsboro sandstone, occurring on the higher hills near this town and at points to the east. The "Niagara" limestone as a whole forms the surface over all but the eastern fourth of the county, with the exception of a few of the higher hills north of Hillsboro and the creek beds along the southern boundary, underlying the higher plateaus east of the lower drift-covered plateau of the Richmond formation.

As in the adjacent counties, the "Niagara" is the best of the water-bearing rock formations, affording large numbers of springs from the top of the shaly layers and nearly everywhere yielding fairly good supplies to wells sunk to the same beds. Considerable

water also occurs in the thick limestone beds independently of the shales, but the supplies are smaller and less certain than those on top of the shale beds. The sandstone forming the top of the formation also doubtless contains water where it is of considerable extent, especially if it is under cover of younger formations. In the part of the county investigated, however, it is found only on one or two of the higher isolated crests, where its water is readily drained away into the adjacent valleys.

"CLINTON" LIMESTONE.

The "Clinton" limestone in Highland County is a semicrystalline pinkish limestone, grading in places into a red limestone or even an impure iron ore, as at Rocky Fork, south of Hillsboro. Its lower part is in many places sandy and in the southern part of the county locally includes a conglomerate. In thickness it ranges from 25 to 50 feet, with an average of about 35 feet. Its outcrop occurs along the western border of the "Niagara" area, as described above, along the sides of the deeper valleys in the southern part of the county, and for several miles along Rocky Fork south of Hillsboro.

The "Clinton," as everywhere else in this part of Ohio, is characterized by numerous springs emerging mainly from its base along the contact with the shaly layers of the underlying Richmond formation and here and there from points higher in the formation. It usually affords a fairly satisfactory source of supply for wells, except when it occurs at the surface without the drift covering. Where it is overlain by the "Niagara," water is usually found in the higher formation, and it is as a rule not necessary for the wells to penetrate to the "Clinton."

RICHMOND FORMATION.

The upper 10 or 20 feet of the Richmond formation is in places a red shale, as at Belfast, on Brush Creek, but is probably more commonly a blue shale. Below this comes a thick series of thin alternating layers of limestone and shale, of which only the upper 50 or 100 feet is exposed in Highland County. The formation occurs beneath the low drift-covered plateau in the western fourth of the county and in the deeper valleys along the southern edge.

The Richmond is not a strong water-bearing formation, but it usually yields enough water to open wells for ordinary domestic and farm requirements, especially where it is overlain by 10 feet or more of drift. Many drilled wells, however, have difficulty in obtaining sufficient water from it. It is of importance in furnishing an impervious layer to retain the waters of the overlying "Clinton."

NOTES BY TOWNS.

HILLSBORO.[1]

Hillsboro, like nearly every other town of importance in southwestern Ohio, sank a deep well in search of oil or gas during the boom in 1887. The well was carried to a depth of 1,750 feet, striking the "Birdseye" at 1,200 feet, or 100 feet below sea level, and obtaining salt water, presumably from the St. Peter sandstone, at 1,750 feet.

A number of springs emerge from the "Niagara" limestone on the uplands near Hillsboro. One of these, which may be taken as a type, is that of J. L. West, 3½ miles north of town. It has a constant flow, independent of seasons, of about 5 gallons a minute, emerging from a bedding plane of the limestone and forming a small pond. A spring house serves also as a dairy. An analysis of the water will be found in the table on pages 204–205.

Hillsboro has a public water supply obtained from eleven wells located near or in the bed of Clear Creek north of town. No pollution seems possible at present, and the water is to be regarded as safer than that from shallower private wells. Other particulars regarding the supply will be found on page 52.

LEESBURG.[1]

Leesburg is located on a drift-covered Niagara plateau most of the wells entering the rock at about 15 feet. All water is from the limestone. The materials encountered are somewhat as follows:

Section in wells at Leesburg, Ohio.

	Thickness.	Depth.
	Feet.	*Feet.*
Drift	15	15
"Niagara" limestone:		
Limestone	85	100
Shale	100	200

A public system was in process of installation at Leesburg in 1906, the supply being obtained from four drilled wells 100 to 200 feet in depth, with sections similar to that given above. The estimated capacity is 100,000 gallons a day. For other particulars the table on page 52 should be consulted.

LYNCHBURG.[1]

Two deep wells have recently been sunk at the Freiberg & Workum distillery, Lynchburg, to depths of about 1,550 feet in search of water,

[1] Conditions in 1906.

but the amounts obtained were so small that an hour's pumping with an air-lift system exhausted the wells. The St. Peter sandstone was entered but was not penetrated far enough to secure the sulphosaline water which is generally encountered at about 300 feet from the top. Shooting the well did not materially increase its yield. The following is a record compiled by the writer from samples furnished by the company.

List of samples from well of Freiberg & Workum, Lynchburg, Ohio.

	Depth of sample in feet.
Richmond and Maysville formations:	
Light-gray calcareous shale	115
Gray argillaceous limestone	180
Light-gray shale and argillaceous limestone	270
Gray argillaceous limestone	420
Dark-gray limestone and gray shale	520
Eden shale: Gray shale and dark-gray limestone	650
Point Pleasant formation:	
Light-gray limestone, highly ferruginous, cemented	850
Nearly black calcareous shale and limestone with some white limestone	920
Gray and white limestone and black argillaceous shale	960
"Birdseye" limestone:	
Light-gray to white limestone and light-gray shale	980
Fine-grained compact grayish limestone resembling lithographic stone	1,100
Same, with slight pink or buff tinge	1,210
Dark compact brownish-gray limestone and gray calcareous shale	1,420
St. Peter sandstone:	
Dark argillaceous and light-gray sandy shale	1,460
Very fine quartzose and biotitic sandstone with a little calcareous cement	1,500
Very fine white to bluff dolomite, ferruginous stains	1,520
Buff to gray dolomite and fine gray biotitic sandstone	1,525
Gray dolomite	1,534

A number of good-sized springs, some of which are utilized by the distillery and others by the town, emerge on the east side of East Fork a mile or more north of town. The distillery springs are four in number and emerge from quicksand, although it seems probable that the water comes mainly from the "Clinton" limestone near its contact with the underlying Richmond formation. The water is piped by gravity to a receiving well at the distillery, from which it is pumped to the works as needed. About 50,000 gallons daily is used from the springs, the remainder being taken from the creek. The water carries some iron and is very hard and seems to be becoming harder. (See pp. 204–205 for analysis.)

The first public supply, derived from a large dug well near town, was installed in 1896, but soon failed. Connection was then made with the infiltration gallery of the distillery, a trench 120 feet long,

15 feet wide, and 15 feet deep, located near town and subject to pollution from surface drainage. A few years later it became necessary for the distillery to use the entire supply, and the town had to seek a new source, which was finally found in a spring north of town, not far from the distillery spring described above. The spring was dug out, cleaned, and inclosed, and the water was piped by gravity to a receiving cistern in town, from which it is pumped to the standpipe. Other data regarding the supply will be found in the table on page 52.

WATER PROSPECTS.

For the purpose of assisting the driller or well owner in determining the underground water conditions in western Highland County the following table has been prepared:

Underground-water conditions in Highland County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Allensburg	Till	40+	Plenty	Richmond	Richmond and Maysville.	Small.
Bell	do	10		"Niagara"	"Clinton"	Usually plenty.
Berrysville	do	10		do	do	Do.
Bridges	do	10		do	do	Do.
Buford	do	25		Richmond	Richmond and Maysville.	Small.
Careytown	do	10		"Niagara"	"Clinton"	Usually plenty.
Danville	do	10		Richmond	Richmond and Maysville.	Small.
Dodsonville	do	2	Fair	do	do	Do.
Fairfax	do	7	Moderate	"Niagara"	"Clinton"	Usually plenty.
Fairview	do	10		Richmond	Richmond and Maysville.	Small.
Fallsville	do	10		"Niagara"	"Clinton"	Usually plenty.
Folsom	do	20	Moderate	do	do	Do.
Gath	do	20		Richmond	Richmond and Maysville.	Small.
Highland	do	100		"Niagara"	"Clinton"	Usually plenty.
Hillsboro	do	10		do	do	Do.
Hollowtown	do	10		Richmond	Richmond and Maysville.	Small.
Leesburg	do	10	Plenty	"Niagara"		
Littleton	do	10		Richmond	Richmond and Maysville.	Do.
Ludwick	do	10		"Niagara"	"Clinton"	Usually plenty.
Lynchburg	do	10–45	Moderate	Richmond	Richmond and Maysville.	Small.
Mowrystown	do	20		do	do	Do.
Needful	do	20		do	do	Do.
Nevin	do	10	Small	do	do	Do.
New Lexington	do	100		"Niagara"	"Clinton"	Usually plenty.
Newmarket	do	8	Fair	do	do	Do.
Pricetown	do	10	Plenty	Richmond	Richmond and Maysville.	Small.
Pulse	do	20		do	do	Do.
Russell	do	10		"Clinton" (?)	"Clinton," Richmond, and Maysville.	Usually plenty.
Samantha	do	20		"Niagara"	"Clinton"	Do.
Strasburg	do			Richmond	Richmond and Maysville.	Small.
Sugartree Ridge	do	8	Moderate	"Niagara"	"Clinton"	Usually plenty.
Taylorsville	do	10		Richmond	Richmond and Maysville.	Small.
Willettville	do	8	Plenty	"Niagara"	"Clinton"	Usually plenty.
Winkle	do	10		Richmond	Richmond and Maysville.	Small.

MIAMI COUNTY (SOUTHERN).

By M. L. Fuller.

Only the southern third of Miami County (the part lying south of an east-west line drawn midway between Troy and Tippecanoe) falls within the area covered by the present report, and it is to this portion only that the following descriptions relate.

SURFACE FEATURES.

Southern Miami County is essentially a flat or gently sloping plateau, standing from 800 to 1,000 feet above sea level, or about 400 to 700 feet above the Ohio. It is cut in the eastern part by the valley of Honey Creek, in the center by the broad valley of the Miami, and in the western part by the sharp but narrow valleys of Stillwater River and its tributaries. The valley bottoms are usually 100 feet or more below the adjacent uplands, or 200 to 250 feet lower than the high, flat divides between the streams. Irregular morainal hills are strongly developed in the southeastern portion, especially along Honey Creek, but are not present over most of the remaining territory.

WATER-BEARING FORMATIONS.

The unconsolidated surface materials include the sandy and gravelly alluvium of the valleys, the pebbly clay of the flat upland surfaces, and the irregular morainal hills of sand, gravel, or pebbly clay of the Honey Creek region. The rock formations immediately underlying the surface deposits in southern Miami County are the "Niagara," "Clinton," and Richmond.

SURFACE DEPOSITS.

ALLUVIUM.

The alluvial deposits are best developed in the valley of the Miami, in which they have a width varying from half a mile at the southern boundary of the county to 2½ miles a little north of Tippecanoe. The thickness of the deposits is unknown, wells 65 feet in depth failing to reach rock even near the edge of the valley, but it is probably at least 100 feet. Along Stillwater River the alluvial deposits are generally less than half a mile in width and are probably less than 50 feet in depth. In southern Miami County both rivers flow in relatively new channels, their older and wider valleys being buried by glacial drift. The old channel of the Miami is probably toward Mad River near Osborn, along the valley of the present Honey Creek, beneath whose irregular morainal hills thick deposits of old alluvium probably exist. A broad channel of the

Stillwater may extend through Kessler and Nashville and along Brush Creek, although wells in this vicinity generally strike rock near the surface. The location of the main channel and alluvial deposits of the preglacial Stillwater, if this river then existed, has not been determined. Many smaller buried valleys and alluvial deposits doubtless occur but have not been traced owing to the lack of sufficient well borings.

The alluvial deposits include gravel, sand, and silt, with perhaps in some places one or more beds of till. In the central portions of the valleys the sands and gravels usually predominate and are saturated with water, but toward the sides the deposits are in places finer and contain less water. Wells can almost everywhere obtain water by sinking to river level, but to insure abundant and safe supplies should be carried at least 20 feet deeper. In few wells is the water under much pressure, and artesian flows are not to be expected.

TILL.

Till is the surface material of the uplands and forms a mantle covering the rock, except at a few points near the rivers, where natural outcrops and cliffs occur. In thickness it varies from 75 feet at places in the uplands to the vanishing point along the edges of the valleys. On the uplands it is in general thinnest in the east, where in many places it measures less than 25 feet, and thickest in the west, where it reaches a thickness of 50 to 75 feet at several points. (See Pl. III.) The variations in thickness are due in part to inequalities of the underlying rock surface and in part to more extensive accumulations toward the west. The till is prevailingly a clay mixed with pebbles and a few bowlders, but in places it is more or less gravelly and may even contain definite beds of sand or gravel. To a depth of 5 or 10 feet it is commonly weathered to a yellowish brown, but at greater depths it is usually gray or bluish. The pebbly clay itself contains relatively small amounts of water but will usually yield enough for domestic use to dug wells. Much more water is found in the interbedded gravel or sand layers, which ordinarily furnish supplies ample for all farm purposes and in some places even sufficient for public supplies. Unfortunately such beds are absent in many places where the till is thin, and there wells have to enter the rock to get water, especially near the valleys, where the water readily drains from the deposits. Where the till is 30 feet or more in thickness, however, adequate supplies will usually be obtained from it. In some wells the pressure is sufficient to lift the water nearly or quite to the surface.

MORAINAL DEPOSITS.

The morainal hills along Honey Creek consist of great numbers of small but steep and very irregular mounds, composed of gravel and

sand and some till, interspersed with deep undrained kettle-like depressions. They commonly rise 60 or 70 feet above the valleys.

The morainal deposits of southern Miami County are composed mainly of porous sands and gravels which permit the water to drain away to the nearest valley or to sink downward into the underlying deposit, which, in the Honey Creek region, is probably alluvium. Wells are generally sunk into this underlying formation at least to the level of the surrounding valleys before procuring satisfactory supplies, and there is rarely any difficulty in obtaining adequate amounts if this is done.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

The "Niagara" limestone is seen in several quarries along Ludlow Creek and, although in few places naturally exposed, appears to underlie the section south of the creek to the county boundary. Little, if any, "Niagara" is present between Stillwater River and Brush Creek, but considerable areas of the formation probably occur on the higher uplands between these streams and the Miami and also east of the Miami. The entire thickness of the "Niagara" is not represented in southern Miami County, there being in few places, if anywhere, more than 50 feet of the formation remaining. Hussy[1] says that the lower part is shaly but gives no localities in the area where such shales exist, and none were seen or reported in the present field work. The rock in the main is a grayish or bluish granular to compact limestone, in places occurring in beds suitable for quarrying.

The "Niagara" generally contains considerable water, especially where covered with thick drift, but in southern Miami County it has no great amount of drift over it and is itself very thin, the lower and nonwater-bearing portion being in many places the only part represented. At Brandt, south of Honey Creek, it is reported as yielding plenty of water to shallow wells, but at Phoneton, near the Miami, and in the area west of Stillwater River, only fair to moderate amounts are reported. On the whole, the "Niagara" in the area under consideration will yield only a fair supply to wells, many of them having to penetrate to the "Clinton" or even to the Richmond to procure the necessary amounts. However, the formation, especially the lower portion, gives rise to many springs, some of which are sources of water for stock or for domestic use.

"CLINTON" LIMESTONE.

The "Clinton" is an irregularly bedded limestone, probably about 35 feet in thickness and somewhat sandy in its lower part. It is readily distinguished by its pinkish color, by its granular or sandy

[1] Hussy, John, Geology of Miami County: Geol. Survey Ohio, vol. 3, 1874, pp. 468–481.

character, and by the cliffs to which it gives rise along the valleys. The steep bluffs which border practically the entire valleys of the Stillwater and Miami in the portion of the county under consideration, are capped by this resistant formation, over which the small tributaries plunge to the valleys below. (See Pl. VII, *B*.) On the uplands between the valleys the "Clinton" is usually covered by drift or by the "Niagara" limestone, and is in few places exposed. What is probably the "Clinton" limestone, however, outcrops at several points on the lower slopes of the upland south of Brown (Rex post office), on Honey Creek.

The "Clinton" is the most important water-bearing formation in the county, being notable throughout the region for the great number of large springs issuing from it. These appear to come from the middle or upper part of the limestone, although a few emerge from its contact with the underlying shale of the Richmond formation, just below the cliffs along the rivers. One of the largest of these springs formerly furnished power for a mill but is now utilized as the public supply of Milton. Along the borders of the valleys only the lower part (which is below the level of the springs) is present, and even this is drained of its water by the deep valleys. Farther back from the streams the "Clinton" will probably afford good supplies to wells.

RICHMOND FORMATION.

The Richmond formation, consisting of thin alternating layers of blue shale and limestone, underlies the alluvium in the valleys of Miami and Stillwater rivers and Honey Creek and is to be seen below the cliffs formed by the "Clinton" limestone in the bluffs bordering the two rivers. In these localities the upper 20 or 25 feet is generally a blue shale, below which the characteristic shaly limestone occurs to the base of the exposures. About 75 feet of the beds occur above the river level at Milton and about 40 feet near Tippecanoe.

The Richmond is not an important water-bearing formation, owing to its large content of shale, which hinders the circulation of the water. It carries, nevertheless, moderate amounts and yields supplies to a number of wells at Fidelity, Ludlow, West Milton, Pigeye, and other places where, because of its thinness or of its drainage by deep valleys, the "Clinton" is unavailable as a source of supply. A few springs emerge at the top of its upper shaly member just below the "Clinton" cliffs.

NOTES BY TOWNS.

TADMOR.[1]

On the Kreitzer property, at the point where the National Road descends the bluff between Phoneton and Tadmor, a small spring

[1] Conditions in 1906.

near the base of the "Clinton" limestone is utilized for operating a ram which lifts the water to the buildings on the bluff above. It is of interest as demonstrating the possibilities of obtaining fine supplies of spring water at the houses along the edge of the bluffs, a situation in which it is difficult to obtain water from wells.

TIPPECANOE.[1]

A deep well sunk at Tippecanoe about 25 years ago in a search for oil and gas. The "Birdseye" limestone was struck at 1,025 feet, or about 180 feet below sea level, but no other data concerning the materials penetrated or the water encountered are available.

The city is situated on the "Clinton" limestone, and previous to 1897 obtained its water from private wells. Owing to the numerous fissures which permitted pollution to enter the wells, many became badly contaminated and the introduction of a public supply became imperative. This is obtained from wells averaging about 60 feet in depth, located on the flats of the Miami; although there are a few houses in the vicinity, there is little danger of pollution owing to the considerable depth (50 feet) to which the wells are carried below the water level. Since the installation of the public supply the private wells have been examined by the health officers at intervals and those found contaminated have been closed and the owners ordered to connect with the public supply. Other information regarding the waterworks and supply will be found on page 52.

WEST MILTON.[1]

West Milton, like Tippecanoe, is situated on the outcrop of the "Clinton" limestone, the fissures of which allow more or less impurities from the surface to penetrate to the wells. The unsatisfactory character of the well water, the cost of drilling, and the need of better fire protection led, a few years ago, to the installation of the present water system, which obtains its supply from Haskett Spring, issuing from the upper part of the "Clinton" limestone about a mile west of town. The water is conducted by a cemented pipe to a receiving well in the village, from which it is pumped to the standpipe. The supply appears to be safe and in every way superior to the water from the wells formerly used. Further particulars are given on page 52 and an analysis on pages 204–205.

Of the numerous springs in the vicinity of West Milton, Haskett Spring, which furnishes the public supply, is the most important. It emerges, as noted above, from the "Clinton" limestone. Its surplus water above that taken for the city supply formed, in August, 1906, a stream 8 feet wide and 4 inches deep, flowing with a velocity

[1] Conditions in 1906.

of 1 foot a second. By adding the equivalent volume to the 135,000 gallons consumed by the city, a total yield of about 1,750,000 gallons daily is obtained. The stream from the spring formerly furnished power to a mill in the town.

WATER PROSPECTS.

The following summary of the underground water conditions will help to determine the prospects of obtaining supplies at the towns and villages in this county:

Underground water conditions in southern Miami County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Brandt	Till, moraine.	12	Plenty	"Niagara"	"Niagara"	Plenty.
Fidelity	do	20	Small	"Clinton"	Richmond	Small.
Ginghamsburg	do	100+	Fair	Richmond	do	Do.
Grayson	Alluvium, moraine.	75+	Moderate	do	do	Do.
Kessler	Till	25	Small	"Clinton"	do	Do.
Laura	do	50	Moderate	"Niagara"	"Clinton"	Moderate.
Ludlow	do	65	Small	"Clinton"	Richmond	Small.
Phoneton	Till, moraine.	20	Moderate	"Niagara"	"Clinton"	Moderate.
Pigeye	Till	3	Small	"Clinton"	Richmond	Small.
Potsdam	do	35	Fair	"Niagara"	"Clinton"	Moderate.
Rex	Till, gravel.	5–50	Moderate	"Clinton"	Richmond	Small.
Tippecanoe	Till	0–10	Small	do	do	Do.
West Milton	do	3	Fair	do	do	Do.

MONTGOMERY COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

To speak broadly, the surface of Montgomery County is a plateau, the plateau characteristics being especially pronounced in the northwest, where very extensive, nearly flat surfaces, broken only by shallow valleys, are found at elevations of 950 to 1,050 feet. In the southern half of the county and in the portion bordering Miami River in the eastern part the plateau character is less distinct, the upland level being broken by the deep valley of the Miami and by the shallower valleys and ravines of its tributaries, between which only relatively narrow-crested ridges remain. Some of these, however, show flat surfaces, having an elevation of 870 to 950 feet, marking the old plateau level that originally extended over the region. The valleys of many of the larger rivers are broad, that of the Miami being from 2 to 3 miles wide in places, although elsewhere, as a few miles northeast of Dayton and near Miamisburg, it is only a quar-

ter to half a mile wide. Tributary valleys vary in width from a few feet to three-fourths of a mile or more, but some of them expand locally to 2 miles or so, for example, Twin Creek in the vicinity of Germantown. The valley sides rise from 100 to 200 feet above the bottoms in the southern part of the county, but in the main have moderate slopes and show few if any rock outcrops. Near the northern edge many of the valleys, although only about half as deep, are broader and are bordered by vertical cliffs, which are very characteristic features of Miami and Stillwater rivers in this region. The valleys slope considerably, descending from 775 feet in the north to 675 feet in the south.

WATER-BEARING FORMATIONS.

SURFACE DEPOSITS.

ALLUVIUM.

The alluvial deposits, as would be expected from the great width of the valleys, are very extensive in Montgomery County, ranging in width from about half a mile near Miamisburg to nearly 4 miles at the junction of Mad and Miami rivers near Dayton. The Stillwater River deposits average three-fourths of a mile in width, those of Mad River between 2½ and 3 miles, and those of the smaller tributaries from a few feet to a quarter of a mile. The depth of the deposits is not known, few if any wells located near the center of the valleys having reached their bottom, though many wells from 50 to 60 feet in depth have been sunk. At Dayton wells have gone 75 feet or more without having found the bottom, and at West Carrollton a well 175 feet deep in the alluvium is reported. It is not improbable that the average depth in the larger valleys is more than 100 feet. Where the streams are flowing in new channels, as is the Miami in the rock-walled valley at the north edge of the county, the depth of the alluvium is probably very much less, possibly not more than 30 feet. The alluvium consists of silt, sand, and gravel, with some included beds of blue pebbly clay or till. The upper 30 or 40 feet of it seems on the average to be somewhat finer and more silty than the deeper beds, in many of which sand or gravel predominates. Till is especially likely to be encountered in the broader valleys, as in the Mad River and Miami bottoms in the vicinity of their junction near Dayton. In this locality many partly buried knolls of till project above the alluvium.

Nearly all wells in the alluvial deposits find water at or slightly above the level of the streams. The deposits from the surface down to 30 or 40 feet are in many places more or less silty, but good water-bearing sands or gravels are generally present at depths of 40 to 60

feet and afford very large supplies of water. Here and there, however, the silty deposits continue to greater depths, and some wells, especially those near the sides of valleys, may have to go down 60 to 90 feet to get adequate supplies. As much as 400 gallons a minute is obtained by some wells in the gravels.

Like all waters in southwestern Ohio, those of the alluvium are hard. They are, however, perfectly pure and suitable for public supplies. The water is clear and free from sediment and is well adapted for paper manufacture, in which it is used at a large number of mills in the Miami Valley.

TERRACE GRAVELS.

Bordering the alluvial deposits at the valley sides at a number of points, especially along Mad and Miami rivers, are low terraces standing from 10 to 25 feet above the flood plains of the streams. They consist very largely of fine to medium gravel, from which the water drains quickly to the adjacent streams or sinks into the underlying formations. For this reason most wells must be carried at least to the level of the nearest stream before they can obtain adequate supplies.

TILL.

The till is a yellowish clay carrying some pebbles and a few bowlders and fragments of wood. Beneath its yellowish upper portion, which is generally 5 to 10 feet in thickness, the till grades downward into gray or blue clay. In the rougher southern portion of the county it is commonly thin, being in many places less than 25 feet thick. It is also thin in the eastern half of the county, especially along the edges of the Stillwater and Miami valleys, in which much bare rock shows at the surface. Within short distances back from the bluffs, however, its thickness increases from 15 to 40 feet. The greatest thickness is in the western half of the county, where the drift is in few places less than 25 feet in depth and in many is 50 feet or more. It is possible that in certain buried channels, as in the vicinity of Brookville, the drift may be considerably more than 100 feet thick. Gravelly or sandy zones or definite beds of sand or gravel are not uncommon, especially in localities where the till is of considerable thickness.

The clayey portion of the till contains considerable water, but yields it rather slowly. Dug wells, however, generally succeed in obtaining moderate supplies. Where gravelly beds are present water is much more abundant, and many driven and drilled wells obtain large quantities. The water is under pressure in many wells. It rises when encountered, but usually does not reach the surface. In

a few places, however, as in the vicinity of Brookville, the water is under sufficient head to produce flowing wells.

MORAINAL DEPOSITS.

Montgomery County is characterized by rather extensive morainal deposits, which in places, especially along the east side of Miami River and the south side of Mad River, reach a thickness of 50 to 100 feet. Generally, however, they are limited to low knolls and disconnected ridges standing not more than 20 to 30 feet above the surrounding surface. The morainal deposits fall into several fairly well defined belts. One extends along the east side of the Mad and Miami valleys from the Greene County line southwestward to the south line of Miami County and along it to the southwest corner. Another less-pronounced belt extends from the Miami in the vicinity of West Carrollton westward through Farmersville to the county line. A third extends from the Miami in the northeastern portion of the county southwestward to the county line, passing just south of Brookville and north of Pyrmont. The deposits do not fall into definite belts, but are scattered irregularly over the general upland surface. The morainal deposits, where thickest, consist to a large extent of gravels and sands, but contain a few beds of pebbly clay or till. In some of the minor deposits till predominates.

Where the morainal deposits consist entirely of sand or gravel they yield very little water to wells, owing to the ease with which they drain into depressions or into the underlying materials. In such places wells, in order to obtain satisfactory supplies, must penetrate to the level of the ground water in the adjacent lowlands. In some places, where layers of till or clay occur in the moraines, the water is prevented from draining away, small amounts being held in irregularities in the clay or till surfaces. Wells reaching such surfaces may obtain supplies sufficient for ordinary domestic or farm purposes. (See fig. 8, p. 41.) Springs not uncommonly occur where the impervious layers come to the surface. In the lower and predominantly clayey knolls the supplies are similar to those of the till, but the wells, being mostly on elevations, have to go somewhat deeper for supplies than on the flats.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

The "Niagara" limestone is found beneath the till in the northern and northwestern portions of the county and also on the flat crests of the high isolated hills representing plateau remnants in the southeastern portion. Except in the north and northwest, however, the

"Niagara" is generally of no great thickness, the few feet which remains being preserved because of the resistance to erosion and weathering of the underlying "Clinton" limestone. The thickness does not seem to exceed 50 feet and in many places is only 5 to 10 feet. At the base of the formation is a few inches of shale, over which lies 5 to 10 feet of limestone suitable for building purposes, known as the Dayton limestone. Above the Dayton are other layers of more irregularly bedded limestone to a thickness of 30 or 35 feet. Some shale probably occurs in places between this and the underlying Dayton. The "Niagara" limestone is usually a gray or bluish granular rock containing a few small cavities, but in some places it is buff and brownish.

The "Niagara" limestone, where overlain by the till, contains considerable water, which it readily yields to dug wells. Owing to the drift covering, springs are not so common at the base of the formation in Montgomery County as they are elsewhere.

"CLINTON" LIMESTONE.

The "Clinton" limestone underlies all the area in which the "Niagara" is found and extends considerably beyond the outcrop of that formation. Large areas occur between Mad and Miami and between Miami and Stillwater rivers, as well as west of Stillwater River to the county line, except perhaps beneath the valley of Wolf Creek. "Clinton" limestone also occurs beneath the "Niagara" on the high plateau remnants southeast of Dayton to the southeast corner of the county. It varies in thickness from 30 feet in the northern portion of the county to 10 feet in the southeastern portion. The lower part is a calcareous sand, and the upper part is a semicrystalline, in places almost marble-like limestone. Its color varies from nearly white, through gray to pink, yellow, and red. The pink or red color, although not predominating, can almost always be seen where any considerable body of the rock is exposed, and it assists in identifying the formation. The bedding is very irregular.

The "Clinton" limestone contains much water and generally yields satisfactory supplies to wells, especially dug wells. It is probably this limestone that yields the water of the public supply at Brookville, which, before the wells were pumped, flowed at the surface. The lower part of the "Clinton" and also to some extent the upper crystalline part give rise to numerous springs, some of them of large volume. The streams formed by these springs may be seen flowing over the bare limestone surfaces and plunging over vertical cliffs at a number of places along the Stillwater (Pl. VII, *B*, p. 45).

RICHMOND AND MAYSVILLE FORMATIONS.

The Richmond and Maysville formations underlie all the lowlands of Montgomery County and in the southern part of the county extend up the hillsides to the base of the "Clinton" at an altitude of nearly 900 feet. Owing to their northward dip, however, they reach an altitude of only about 800 feet near the northern border. They probably underlie most of the uplands up to a point about 2 miles south of Brookville. The upper 6 to 20 feet is a reddish or yellowish shale, but below this shale thin layers of limestone and shale, generally from 2 to 10 inches in thickness, alternate down to the valley level. Probably somewhat over 200 feet of these beds is exposed in the county.

Owing to the thinness of the limestone beds and the scarcity of solution passages, as well as the absence of porous layers, the Richmond and Maysville are not strong water-bearing formations. Where covered, however, by 10 to 20 feet of drift, which serves to hold and feed the water to the upper part of the series, fair supplies are obtained by many dug wells. Few drilled wells in these formations are successful.

NOTES BY TOWNS.

BROOKVILLE.[1]

The public supply at Brookville has been installed only a few years and is not yet so generally used as it should be in view of its much greater safety compared with the average private well, especially the shallow-dug well. It is derived from four 80-foot wells sunk through a considerable thickness of clay and other material, shutting off polluting matter, into the underlying limestone. The water would flow at the surface if not pumped. Other particulars of the supply will be found on page 52.

CHAUTAUQUA GROVE.[1]

The Chautauqua Grove summer resort and camp-meeting grounds are supplied from six driven wells, sunk about 25 feet in the river alluvium. The water is used for drinking and other domestic purposes, supplying without difficulty the campers and visitors, who at times number nearly 5,000. It is pumped by a gasoline engine for flushing and other purposes.

DAYTON.[1]

Dayton is situated mainly upon the broad flats at the junction of Miami and Mad rivers, but the outskirts of the city rest on terraces somewhat above the flood plain, even extending up the slopes of the

[1] Conditions in 1906.

surrounding rock hills. The public water supply has been in use for many years and supplies by far the greater portion of the population, few private wells being used, except those at the large industrial establishments and those on the outskirts.

Most of the wells now in use are in the lower part of the city and consist of 4 to 8 inch pipes driven 40 to 70 feet to gravel beds in the soft alluvial deposits. Abundant supplies are nearly everywhere obtained, although where the sands are unusually fine or silty only moderate amounts may be found. On the hills shallow dug wells obtain fair supplies from the drift or upper part of the rock, but deep drilled wells are almost invariably failures, the Richmond formation, which they penetrate, being almost destitute of water. One well on the hill above the town was carried to 800 feet without success. Additional data regarding the wells will be found on page 52 and analyses of the waters on pages 204–205.

Several wells were put down in search for oil and gas in 1886 and 1887. One of these, located at the corner of Brown and Cemetery streets, afforded the following record:

Record of deep well at Dayton.[a]

	Thickness.	Depth.
	Feet.	*Feet.*
[Drift]	40	40
Richmond and Maysville formations: Blue limestone	420	460
Maysville formation and Eden shale: Blue slate, dark at bottom	415	875
Point Pleasant formation:		
Sand (?)	25	900
Limestone interstratified with shale	80	980
"Birdseye" limestone:		
White limestone	30	1,010
Blue limestone	10	1,020
Brown limestone	280	1,300
Limestone and shale	120	1,420
St. Peter sandstone (?):		
White sand	10	1,430
White siliceous, calcareous, and magnesian rock	250	1,680
Cambrian and Ordovician dolomite: White magnesian limestone	760	2,440

[a] Orton, Edward, Geol. Survey, Ohio, vol. 6, 1888, p. 286. Correlations by M. L. Fuller.

Some water was found in the upper parts of the boring, the casing of which was carried to 425 feet. Salt water was struck in the "Birdseye" at 1,360 feet and in the St. Peter at 1,450 feet. The water rose within 200 feet of the surface from the lower bed. The top of the "Birdseye" is about 115 feet below sea level. Some gas was obtained.

Another well sunk at the corner of First and Finlay streets reported 247 feet of unconsolidated deposits, mainly gravel. The first public supply at Dayton was installed in the city in 1869, the water being obtained from Mad River, but this supply was replaced in 1887 by a system of wells driven 30 to 60 feet in the alluvium

bordering Mad River, just above the city. In 1906 seventy-seven 8-inch wells were in use, and seventeen had been abandoned. The wells extend along the river bank for 4,000 feet, the pumping station being near the middle. In 1906 a new supplementary system was about to be installed to serve the higher parts of the town and the residences on the surrounding hills. It was planned to obtain water from wells near the old plant and to raise it to the required level, 200 feet above the station, by high-pressure pumps. No sewage enters Mad River above the wells, but it receives some water from strawboard works. Unless, however, the entire ground water of the vicinity is lowered 30 to 60 feet below the surface and the river water drawn down to the level of the bottom of the wells, a condition not likely to result, there is little danger of pollution from the source mentioned. If, however, large quantities of sewage or other waste entered the valley from the sides it would be liable to work its way toward the river and contaminate the wells. If such contamination ever occurs the remedy will be to sink wells to 100 feet or more instead of 30 to 60 feet, as no pollution is likely to reach the greater depth. Further particulars of the public supplies will be found on page 52.

The National Military Home, a few miles west of Dayton, has an independent water supply from sixteen 6-inch steam-blown wells (see p. 52), penetrating a gravel lying at the base of the drift at depths of 45 to 58 feet. The wells are 1¼ miles east of the home, and from them the water is pumped to a reservoir. Other particulars will be found on page 52.

FARMERSVILLE.[1]

Farmersville has 8 or 10 drilled wells, the supplies being obtained from sand and gravel beneath a bed of blue clay or till that underlies the surface morainal deposits. The wells are said to range from 78 to 168 feet in depth. A field analysis of the water will be found on pages 206–207.

GERMANTOWN.[1]

Germantown is without a public water system, notwithstanding the fact that it is so situated that a supply could probably be procured from wells at a relatively small cost, the broad alluvial flats of Twin Creek, upon which the town is situated, carrying abundant water within a short distance of the surface. The wells should preferably be of the driven type and should be carried to a depth of not less than 60 feet in order to be safe from pollution. The supply would probably be of good quality and would be a great improvement over that afforded by the common shallow surface-water wells. The gain in convenience and in security against fire would also be factors of great importance.

[1] Conditions in 1906.

MIAMISBURG.[1]

The ground-water conditions are somewhat variable at Miamisburg. Near the center of the valley most of the wells get abundant supplies from the alluvium, but near the base of the hills water is often difficult to obtain, owing to the more silty character of the deposits and to the slight depth to rock. On one lot six unsuccessful attempts to procure water were made, although in the neighborhood all wells obtained water. West of the railroad most of the wells are driven, but east of it drilling must be resorted to.

Two wells, one 1,300 feet and the other 800 feet in depth, were drilled during the oil boom, in 1887. Considerable volumes of gas were encountered, but not enough for permanent commercial purposes. In the deeper well a sulphurous brine was encountered in large quantity at the bottom, presumably in the St. Peter sandstone, rising within 300 feet of the surface. The record of the 800-foot well is as follows:

Record of deep well at Miamisburg.[a]

	Thickness.	Depth.
	Feet.	*Feet.*
Drift: Mainly gravel	181	181
Richmond and Maysville formations:		
Blue slate	260	441
Lighter slate	40	481
Eden shale: Dark shale, becoming black	220	701
Point Pleasant formation: Limestone and shale	99	800

[a] Orton, Edward, Geol. Survey, Ohio, vol. 6, 1888, p. 289. Correlations of formations are by the author of this report.

The town of Miamisburg has recently installed a public waterworks, the water being obtained from wells sunk in the alluvium near the base of the hills at the southeast edge of town. There are no buildings in the vicinity and no chance of pollution at the present time. The supply is claimed to be ample for the needs of the town, although the water at the point where the wells are located seems to be less abundant than in the wells in the center of the valley. If at any time the wells should fail and it should be necessary to seek a new locality, a spot located above rather than below the town and near the center of the valley rather than toward the side should be selected. Other particulars regarding the wells will be found on page 52.

OAKWOOD.[1]

Oakwood has a public supply derived from two flowing wells. It is extensively utilized, but a few private wells are still used. Other particulars will be found on page 52.

[1] Conditions in 1906.

TROTWOOD.[1]

Trotwood is one of the smallest villages in the county having a public water supply, the installation following a destructive fire in 1899. It is owned by a private stock company and obtains its supply from two 6-inch wells sunk to a bed of gravel below the till. The water from the wells, together with compressed air, is pumped by a gasoline engine into a horizontal steel tank, in which it is held under a pressure of 40 to 80 pounds. The water is used for extinguishing fires, sprinkling, and washing, but is not popular for drinking, owing to the length of time it stands in the tank. It appears, however, to be perfectly safe. Further statistics are given on page 52 and a partial analysis on pages 206–207.

UNION.[1]

Union is located on the outcrop of the "Clinton" limestone, only a thin covering of drift overlying the rock surface. Open wells, which generally go through the limestone into the underlying shale, commonly find moderate supplies, the limestone affording the water, which is stored in the lower part of the well in the impervious shales. Drilled wells are much less successful, as they draw mainly from the relatively dry shale. Wells of both kinds are liable to contamination by the entrance of polluting matter through fissures in the limestone. The record of one of the deeper wells is given below. A partial analysis of the water will be found on pages 206–207.

Record of Eby well at Union.

	Thickness.	Depth.
	Feet.	*Feet.*
"Clinton" limestone: Limestone	15	15
Richmond formation:		
Blue clay	7	22
Gray rock	10	32
Blue clay and rock	35	67
"Drift rock" (cavernous rock?)	12	79
Blue clay	6	85
Gray rock	8	93

WEST CARROLLTON.[1]

The public waterworks at West Carrollton was installed by the village in 1897, the water being obtained from wells driven 60 to 80 feet in the sand beneath the lowlands along the Miami & Erie Canal and pumped by the G. H. Friend Paper & Tablet Co. into the mains. The well water is free from pollution and suitable for all domestic purposes. Additional particulars regarding the supply will be found on page 52; an analysis of the water is given on pages 206–207.

[1] Conditions in 1906.

WATER PROSPECTS.

Underground water conditions in the villages and towns of Montgomery County are summarized in the following table:

Underground-water conditions in Montgomery County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Air Hill	Till	50		"Clinton" (?).	"Clinton" (?)	Usually plenty.
Alexandersville	Alluvium	30+	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
Amity	Till	60		"Clinton"	"Clinton," Richmond, and Maysville.	Moderate.
Arlington	do	40	Plenty	"Niagara"	"Clinton"	Usually plenty.
Bachman	do	50	do	do	do	Do.
Beavertown	do	13	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Bridgeport	Alluvium	Deep.	do	do	do	Do.
Brookville	Till	70	do	"Niagara"	"Clinton"	Usually plenty.
Centerville	do	12	do	"Clinton"	"Clinton," Richmond, and Maysville.	Moderate.
Chambersburg	do	40	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Clayton	do	30	do	"Niagara"	"Clinton"	Usually plenty.
Crown Point	do	40		Richmond and Maysville.	Richmond and Maysville.	Small.
Dayton	Alluvium	70+	Plenty	do	do	Do.
Dean	Till	35		do	do	Do.
Dodson	do	60	Plenty	"Niagara"	"Clinton"	Usually plenty
Drexel	do	60		"Clinton"	"Clinton," Richmond, and Maysville.	Do.
Ebenezer	do	50		Richmond and Maysville.	Richmond and Maysville.	Small.
Ellerton	Till, moraine	40		do	do	Do.
Englewood	Till	10	Small	"Clinton"	Richmond, "Clinton," and Maysville.	Moderate.
Fairmount	do	12	Plenty			
Farmersville	Till, moraine	140+	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Fort McKinley	Till	100+	do	do	do	Do.
Fourmile House	do	12	do	"Clinton"	"Clinton," Richmond, and Maysville.	Moderate.
Germantown	Alluvium		do	Richmond and Maysville.	Richmond and Maysville.	Small.
Gettersberg	Till	35	Moderate	do	do	Do.
Happy Corners	do	35		"Clinton"	"Clinton"	Usually plenty.
Harshman	Alluvium	Deep.	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
Hayes Store	Till	11	do	"Clinton"	"Clinton"	Usually plenty.
Kingsville	do	35	Moderate	do	"Clinton," Richmond, and Maysville.	Moderate.
Kinsey	do	20	Plenty	do	"Clinton"	Usually plenty.
Kreitzer Corner	do	100+	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Lambertine	do	40		do	do	Do.
Liberty	do	20		do	do	Do.
Little York	do	25		do	do	Do.
Miamisburg	Alluvium	60+	Plenty	do	do	Do.
Mummaville	do	50+	Variable	do	do	Do.
National Military Home	Till	60+	Plenty	do	do	Do.
New Lebanon	do	60	do	do	do	Do.

Underground-water conditions in Montgomery County—Continued.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Phillipburg	Till	30	Fair	"Niagara"	"Clinton"	Usually plenty.
Pyrmont	do	60	Plenty	do	do	Do.
St. Richmond	do	60	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Sixmile	do	20	do	do	do	Do.
Spanker	do	16	do	do	do	Do.
Sulphur Grove	do	20	do	"Niagara"	"Clinton"	Usually plenty.
Swanktown	do	60	do	do	do	Do.
Tadmor	Alluvium	80+	Fair	Richmond and Maysville.	Richmond and Maysville.	Small.
Taylorsburg (on Dry Run).	Till	40	Plenty	do	do	Do.
Taylorsburg (on Miami River).	Alluvium	Deep.	do	do	do	Do.
Trotwood	Till	50	do	do	do	Do.
Union	do	3	Small	"Clinton"	"Clinton," Richmond, and Maysville.	Moderate.
Vandalia	do	30	Moderate	"Niagara"	"Clinton"	Usually plenty.
Verona	do	40	Plenty	do	do	Do.
Vorhees	do	40		do	do	Do.
Wengerlawn	do	60		do	do	Do.
West Carrollton.	Alluvium	80+	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
Woodbourn	Till	25	Small	do	do	Do.

PREBLE COUNTY.

By Frederick G. Clapp.

The following description applies to all of Preble County except the quarter lying north and northeast of Eaton, which could not be examined during the short time spent in the field.

SURFACE FEATURES.

The surface of Preble County is rather diversified in its features, depending on the distribution of the glacial drift. Most of the northern portion consists of a plateau-like surface, having a maximum elevation of about 1,250 feet along the western border and descending to about 1,050 feet on the eastern border. In the southern part of the county the surface is more diversified, the hills being somewhat dissected by streams, whereas the uplands in the northern part of the county are broad and flat and contain few streams. The creeks descend from shallow depressions on the uplands into deep and narrow valleys, with flood plains ranging from a few hundred feet to a quarter of a mile in width. The larger streams—Banta, Twin, Sevenmile, and Fourmile creeks—descend to elevations of 700 to 800 feet on the southern and eastern borders of the county. The valley flats consist of alluvium. The county is crossed in a general northwest-southeast direction by three broad morainal ridges.

WATER-BEARING FORMATIONS.

SURFACE DEPOSITS.

ALLUVIUM.

As the streams of Preble County are not large, their deposits are not very extensive. Twin, Banta, Sevenmile, and Fourmile creeks have flood plains reaching, in places, a width of a quarter of a mile or more. They are generally flat and low and lie between steep bordering hillsides. The surface portion of the alluvium is mostly fine, with sands and silts predominating, but well sections show that in many places coarse gravels lie below the surface.

Except where it is very thin, the alluvium generally yields satisfactory water supplies to driven wells, especially in the deeper and broader valleys. At Eaton such wells are sunk to a considerable depth in alluvium and furnish the public supply.

TERRACE GRAVELS.

Narrow deposits of coarse gravel border some of the principal streams, where they rise to heights of 50 to 100 feet above the bottom of the valley and form flat terraces. Water on these terraces is generally scanty, the supply draining out on the sides to the valleys.

TILL.

The greater portion of Preble County, as of other counties in the vicinity, is covered by pebbly clay or till of varying thickness, which is rather uneven in its distribution, in some places overlying gravels and in others underlying them. Generally, however, a considerable thickness of till overlies the bedrock of the region, and beds of till, generally called hardpan by the drillers, are penetrated in sinking deep wells. Along many creeks can be seen deep sections of till, in some places only a few feet in thickness and in others 100 feet or more thick. Where characteristic the till is hard and compact and contains many pebbles and in places large bowlders. The upper 5 to 10 feet may be yellowed by oxidation, but the underlying portion is generally blue-gray. Over most of the county there are at least two beds of till, the one resting on bedrock being the more clayey, solid, and tough, and the one forming the surface or lying near it being generally looser, with a larger proportion of bowlders and sand.

The water supplies of the till are, as a rule, not large. Wells sunk in it may obtain plenty of water during the greater part of the year, but the supply is liable to become exhausted in summer. The old-fashioned dug or open wells are most successful in the till, as driven wells are generally not of large enough diameter to form a sufficient reservoir for the water which seeps in from the surrounding till. The open wells, however, are not so safe from pollution as those of other types.

MORAINAL DEPOSITS AND OUTWASH PLAINS.

Under morainal deposits and outwash plains are included the deposits which in general overlie the thicker or deeper of the two till sheets. They include, first, broad undulating morainal deposits of sand and gravel, which are easily recognizable by their surface features, and, second, broader and flatter deposits of sand and gravel, which in places stretch for many miles with a surface apparently as level as a floor, and which are made up of fairly horizontal beds of sands and gravel overlain only by superficial till a few feet in thickness. The thickness of these plains deposits is in places very great. They are believed to be best developed on the uplands within a few miles of Eaton.

The true moraines of Preble County consist of three principal belts. The outermost, a mile or two wide, enters the county near its southeast corner, runs westward to Camden, crosses Sevenmile Creek, takes a north-northwesterly sweep, and strikes the northwest corner of the county north of New Paris. The second moraine is not so conspicuous and, except at its east end, is broader and flatter. It enters from Montgomery County south of West Alexandria, sweeps northward, passing between West Alexandria and Eaton, and at the northwest corner of the county merges with the outer moraine. The third line of moraines, which is still less conspicuous, crosses the northeast corner of the county northeast of Lewisburg.

In the morainal deposits of the typical hilly type, such as those in the outer belt, it is necessary to drill to a considerable depth to reach water. On the inner moraines, however, and on the broad flat areas surrounding them, water has less chance to drain away and is encountered at several depths below the surface, the different water beds being known accordingly as the "first," "second," and "third." In the vicinity of Eaton and elsewhere flowing artesian wells have been obtained by short pipes driven into these deposits, and near West Alexandria deep-driven wells obtain flows from them.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

Probably more than half of the bedrock in Preble County consists of "Niagara" limestone. The "Niagara" constitutes the entire area north, northwest, and west of Eaton, extending southward almost uninterruptedly beyond Sugar Valley, whence a strip of it, with an apparent width of more than a mile, stretches southward between Sevenmile and Fourmile Creeks nearly to the edge of Butler County, southeast of Morning Sun. Another arm of the "Niagara" limestone stretches southeastward from Eaton nearly to Winchester. In the southeast corner of the county there are only a few scattered

patches of it. The "Niagara" covers most of the northeast quarter of the county but is not present along the valley south of Lewisburg.

In the northwest corner of the county, on the uplands, the "Niagara" limestone may be over 100 feet in thickness, but where it outcrops in the southern part of the county it has in places a thickness of only a few feet, the rest of it having been eroded.

The "Niagara" is quarried for building stone in a number of places, one of which is near a shallow creek about 2 miles northeast of Eaton. The most important quarries, however, are at New Paris, in the northwest corner of the county, where the workings are 30 or 40 feet deep and the rock makes excellent building stone.

The "Niagara" limestone probably contains more water than any other of the rock formations lying near the surface in Preble County. It is generally a bedded or massive gray to buff limestone. Some water is found in it by shallow wells, but the greatest amounts are generally obtained by deep wells which penetrate nearly to the top of the underlying "Clinton" limestone. The "Niagara" limestone contains a great many irregular solution passages, through which water is flowing, and when these passages are tapped by the drill they yield a large amount of water. (See Pl. V, *A*.)

"CLINTON" LIMESTONE.

The "Clinton" limestone underlies the entire area in which the "Niagara" is found and extends somewhat beyond the outcrop of that formation. Owing to the thick drift covering in Preble County, little of the "Clinton" is believed to be exposed, but it can be seen in a few places along the uplands west of Sevenmile Creek and probably at other points. Owing to the scarcity of exposures and to the fact that in well records it is generally reported with the "Niagara" simply as "limestone," its thickness is not known with certainty, but it is believed to measure not over 50 feet. Where characteristic, it consists of massive buff to pinkish, horizontally or cross bedded limestone, composed largely of minute shell fragments.

Although the "Clinton" limestone can not be differentiated from the "Niagara" where penetrated by wells, the fact that many wells find water near the base of the material reported as limestone seems to indicate that the "Clinton" yields moderate amounts. Generally, however, it acts as an impervious bed; along its upper portion numerous springs issue from the "Niagara" limestone.

RICHMOND AND MAYSVILLE FORMATION.

The lowlands in southern Preble County, as far north as Fairhaven on Fourmile Creek, nearly to Eaton on Sevenmile Creek, and as far as Lewisburg on Twin Creek, consist of the Richmond and

Maysville formations, which form the bottoms of the valleys and extend for considerable distances up the hillsides. In the southern part of the county these formations form many entire hills, except perhaps for a thin capping of "Clinton" and "Niagara" limestones.

Owing to the fact that the county is so thickly covered by drift, little can be said of the lithologic character of the Richmond and Maysville formations. Doubtless it is similar to that of these formations as seen in Butler and other counties, where they consist of 1 to 10-inch layers of interstratified shale and limestone.

Owing to the thinness of the limestone beds and the consequent scarcity of solution passages, the Richmond and Maysville formations contain only a moderate amount of water. They yield very little to shallow wells, and practically none to most drilled wells. Where water is found it is generally inferior in quality to that in the "Niagara" and "Clinton" limestones and in some wells is sulphurous or brackish.

NOTES BY TOWNS.

CAMDEN.[1]

Three gas wells have been sunk by the town of Camden. One of them is 85 feet deep; the depths of the others are unknown. One well still yields gas, under 35 pounds pressure, which is used for running an engine and which was at one time piped all over the town.

One of the gas borings penetrated 180 feet of drift before reaching bedrock, showing that a deep buried valley extends northward from the Miami Valley and was formerly occupied by a stream of considerable size.

CEDAR SPRINGS.[1]

About a mile south of New Paris is the Cedar Springs Hotel, a popular summer resort on the New Paris and Westville branch of the Dayton & Western Electric Railroad. The Cedar Springs, several in number, are situated in the valley near this hotel. They are dug 6 or 8 feet in the bottom of the valley near a small run. The water occurs in gravel underneath hardpan, and one of the springs extends into the "second-gravel" bed. The hardpan and gravel layers rise into the morainal hills in the opposite direction from the hotel, and for that reason there is no danger of pollution; moreover, excellent sanitary precautions are taken in the curbing of the springs. The springs, which are known individually as the Navahoe, Iron, Glycerine, and Cathartic springs, have been analyzed (see pp. 206–207), and the composition of the water seems to depend on whether it occurs in the "first" or "second" gravel. Around several of the springs there is a slight iron stain, due to the iron in the water. The volume of flow

[1] Conditions in 1906.

can not be conveniently measured, but is estimated at 5 to 10 gallons a minute. The surroundings of the springs are thickly wooded. In addition to being used at the summer hotel, the water is bottled for shipment to a distance as "Navahoe water," though all of it does not come from Navahoe Spring. These springs have a history dating back to the days of the aborigines, and great medicinal value is claimed for them.

EATON.[1]

Public supply.—Eaton has a fair public supply, derived from drilled wells 6 inches in diameter, sunk on the flood plain of Sevenmile Creek west of the village within 50 rods of the pumping station. The system was installed in 1891. In all, ten wells have been sunk to depths of 60 to 100 feet, but only two are used. These are pumped with an air lift. A sample record is as follows:

Record of driven well of the Eaton Waterworks.

	Thickness.	Depth.
	Feet.	*Feet.*
Soil	4	4
Hardpan	55	59
Coarse blue gravel	20	79

This is believed to be an average record. Under the blue gravel is another bed of "hardpan," and bedrock is entered at depths of 57½ to 99 feet. Several of these wells found very little water on account of the fine-grained nature of the sediments penetrated. The wells which are in use will sometimes overflow after standing several days without pumping. By pumping the two wells 18 hours a day an average of 120,000 gallons of water is obtained. The water is delivered by an air lift from the wells to a cistern at the pumping station and then pumped to a standpipe whose top is 150 feet above the station or 135 feet above Main Street. During the summer the supply is insufficient and it is necessary to stop lawn sprinkling, etc. For this reason it has been suggested that the mains be extended to some springs situated a short distance up the creek. The composition of the water is given on pages 206–207.

In 1894 a 10-inch pipe-line was run 1,500 feet west from the pumping station to a spring at the foot of a bluff across the creek. While the surface was wooded plenty of water was obtained, but since much of the forest has been cut away the spring has failed and has been abandoned. Water was also drawn from two cisterns and 24 rods of tile at the base of the bluff, being obtained mostly from a bed of water-bearing gravel 4 feet thick which outcrops 14 feet below the

[1] Conditions in 1906.

top of the bluff. Only about one-tenth the original supply is now obtained.

Flowing wells.—In the northeast corner of Eaton a number of wells bored with an auger in sand and gravel to depths of 25 to 35 feet flow as "fountains." The wells were sunk about 1820[1] and recently the flow in all of them has diminished greatly owing to the sinking of new wells. The water has a temperature of 52° and contains iron, but it otherwise of good quality and is satisfactory to the residents in that part of town. The water, which will rise several feet above the surface, comes from gently inclined gravel beds in the morainal deposits which rise gradually toward the northwest.

Drilled wells.—A number of drilled wells have been sunk at Eaton. Two of them, 186 and 326 feet deep and 8 inches in diameter, are situated at the plant of the Eastern Electric Light & Power & Ice Manufacturing Co. They obtained very little water, probably because they were mostly in the Richmond and Maysville formations. Rock was struck at 24 feet.

Several wells in the village seem to furnish water of excellent quality. One of these is a dug well at the courthouse.

Several attempts have been made to find oil and gas in the vicinity of Eaton About 1885 a deep well, sunk on the William Acherman lot, penetrated the "Birdseye" limestone and a bed of sandstone and obtained salt water. It is reported to have been about 1,600 feet deep and was cased for about 300 feet; the record, however, has been lost. Another test well, about 1,200 feet deep, was put down at the electric-light plant, then owned by Josiah N. Robinson. Persons who were interested in the borings report that the "Birdseye" limestone dipped markedly from the Acherman well toward the well at the electric-light plant.

Springs.—In the vicinity of Eaton there are a number of springs of considerable importance. One of them, situated at the picnic grounds about a mile southeast of the village, issues from the foot of a slope about 5 feet above a run in a shallow ravine with a flow estimated at about 3 gallons a minute. It is supposed to come from the "Niagara" limestone.

Four miles northeast of Eaton, on the Lewisburg Pike, an enormous spring issues from drift deposits in a slight depression. The water bubbles up from sand with an estimated volume of at least 50 gallons a minute. This is the largest spring known in the county.

[1] History of Preble County, Ohio, H. Z. Williams & Bro., 1881, p. 134.

LEWISBURG.[1]

Lewisburg is situated on a gentle till slope, rising from Swamp Creek. The base of the "Niagara" limestone outcrops along the bluffs bordering the creek, but on the plain the rock is covered by 10 to 20 feet of till. Most of the wells are the old-fashioned dug wells, but some of them are drilled.

Most of the drilled wells yield water of good quality. Probably the deepest well in Lewisburg is that at the Handle (?) factory. It is 101 feet deep and strikes limestone 15 feet from the surface. The water tastes very strongly of sulphur. It can not be exhausted with a steam pump. About a mile north of Lewisburg a well was drilled 185 feet, nearly all in solid rock. In the surrounding country there are a number of drilled wells that are not so deep.

A gas well drilled on the eastern border of the village to a depth of about 1,300 feet is reported to have struck the "Birdseye" limestone at 950 to 1,050 feet and to have found an abundance of salt water. A fine supply of water was struck about 300 feet from the surface and was used in drilling. A little gas was obtained from the shale and is still used, but none was found in the "Birdseye."

NEW PARIS.[1]

At New Paris rock outcrops at the surface, but its extremely irregular character is shown by the fact that about a mile north of the village a well is reported to have been sunk to a depth of 285 feet before striking rock. No water was found. Other deep wells in the drift show that there are deep gravel-filled valleys in this neighborhood which represent the former courses of the streams. It is probable that East Fork of Whitewater Creek once followed a course very different from its present one.

C. W. Bloom, of New Paris, draws a small public supply from a dug well 17 feet deep in gravel below "hardpan." The well can be pumped at the rate of 125 gallons a minute and the water is of excellent quality. Analysis is given on pages 206–207.

The largest limestone quarries in the northwestern part of the county are at New Paris, the most important one now in operation being that of Reinheimer Bros., near the south end of town. The "Niagara" limestone at this place is overlain by till ranging from a few inches to 4 feet in thickness. The limestone here is a fine-grained bluish-gray rock containing numerous layers of "flint rock" up to a foot in thickness and some flint nodules. The joints in the limestone are, in general, tightly closed. Two systems exist, one running east and west and the other north and south. The cracks are nearly vertical. Throughout the limestone many small solution

[1] Conditions in 1906.

passages follow the joint cracks, forming channels for several springs of excellent quality, which issue from the rock. One flows from a solution cavity about a foot in diameter with an estimated volume of 2 or 3 gallons a minute. The most interesting spring is at the south end of the quarry, where (Pl. V, *A*, p. 36) a conspicuous solution channel a few inches in diameter follows the rock vein along the joint crack for several rods. During the quarrying operations within the last few years the spring has been traced downward into the hill for a distance of about 500 feet. The volume of flow is now about 7 gallons a minute but is diminishing as the quarrying operations progress. The water is of excellent quality and is used by the workmen for drinking. The measured temperature is 52°. Analyses of springs in this quarry are given on pages 206–207. These springs and solution channels furnish a clue to the probable mode of occurrence of well water in limestone at great depths below the surface and show that wells sunk in the "Niagara" limestone may be expected to find moderate or even large amounts of water of good quality by striking one of these solution channels. If, on the other hand, as sometimes happens, they do not chance to strike a vein of water, the well will be unsuccessful.

WEST ALEXANDRIA.[1]

West Alexandria has a public supply owned by the village. The system consists of four drilled wells 134 feet in depth. A record of the strata passed through is as follows:

Section of deep wells of West Alexandria waterworks.

	Thickness.	Depth.
	Feet.	*Feet.*
Clay (till containing numerous large bowlders)	16	16
Gravel (containing water)	13	29
Blue clay	31	60
Gravel (containing water)	12	72
Hardpan	49	121
Quicksand	7	128
Gravel (containing water)	6	134

The water used comes from the gravel bed at the bottom. The well of which the record is given above was the last to be installed in the system and was drilled in January, 1905. Originally the town had wells 65 and 95 feet deep, but enough water was not obtained from them, and drilling was carried into the "third gravel." The water in the "second gravel," which was originally used, rose nearly to the surface. The actual yield is not known, but nearly 1,000 gallons a minute has been obtained without lowering the water over 4

[1] Conditions in 1906.

feet from the surface. The amount pumped ordinarily is reported as about 35 gallons a minute. The wells are arranged in the form of a square 400 feet on a side. From them the water is pumped to a standpipe 119 feet above the pumping station and 100 feet above the ground. The system is reported very satisfactory.

Several flowing wells have been obtained in West Alexandria. The best three were sunk for S. S. Black near the south end of the village. Two of them were 112 and 121 feet deep, but only one of these is now in use, the second well being drilled when the first one was accidentally ruined. This well is the finest flowing well in the county, and Mr. Black uses it to supply a fountain which stands in his front yard and a fishpond covering half an acre. The water is also used for all domestic purposes. It will rise unconfined 14 feet above the surface. The temperature is 52°. Mr. Black's third well is 112 feet deep and supplies a canning factory. The water will rise 12 feet from the surface and is piped to the second story of the factory. The water in these wells comes from some of the deeper gravels of morainal deposits and probably owes its head to a long descent along beds dipping from the north or northwest.

WEST ELKTON.[1]

True flowing wells are not known in the vicinity of West Elkton, but at the west end of the village Elijah Mendenhall has a dug well 16 feet in depth, from which the water flows in a constant stream through a pipe connected with the well 4 feet below the surface. This water is very high in iron. (See analysis, pp. 206–207.) The morainal hill on the side of which this well is situated rises about 40 feet higher within 400 feet north of the well, and the head is believed to be due to the presence of an inclined gravel bed.

WEST MANCHESTER.[1]

West Manchester is situated on a very flat till plain several miles broad. Part of the residents use the public supply, but some still use dug wells 20 to 40 feet in depth. Many of these are in poor locations and the sanitary quality of their water is doubtful. The public supply is excellent and should be more widely used.

Data regarding the public supply are given on page 52. The waterworks, which were installed in 1903–4, are situated on the plain at the southeast corner of the village and consist of a small pumping station and three drilled wells. The water is pumped from the wells each morning into two large tanks, 36 by 8 feet. The tanks are filled about half full, compressing the air above, and the water is distributed by the consequent pressure, which ranges from 25 to 55 pounds.

[1] Conditions in 1906.

Before the waterworks were installed a test well was sunk to a depth of 150 feet. It is reported to have struck rock at 70 to 80 feet, but some of the inhabitants doubt whether rock was really struck. As no water was found below 65 feet the well was abandoned below that depth.

The water in the wells stands about 10 feet below the surface without pumping and can not be pumped down below 23 feet.

WATER PROSPECTS.

The underground-water conditions in the several cities and villages in Preble County are summarized in the following table:

Underground water conditions in Preble County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water bearing rocks.	Water supply.
		Feet.				
Camden	Alluvium	Deep.	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
Campbellstown	Moraine			"Niagara"	"Niagara"	Plenty.
Eaton	Moraine and till.	40 to deep.	Plenty	do	do	Do.
Eldorado	Moraine	80–100	do	do	do	Do.
Euphemia	Till	0–20	Moderate.	do	"Niagara" and "Clinton."	Do.
Fairhaven	Alluvium	15	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Gettysburg	Moraine and till.			"Niagara"	"Niagara"	Plenty.
Greenbush	Till	6	Moderate.	Richmond and Maysville.	Richmond and Maysville.	Small.
Ingomar	Moraine			do	do	Do.
Lewisburg	Till	10–20	Moderate.	"Niagara"	"Niagara" and "Clinton."	Plenty.
Morning Sun	do	Shallow.	do	Richmond and Maysville.	Richmond and Maysville.	Small.
Oklahoma	do	+30	Plenty	"Niagara"	"Niagara"	Plenty.
New Hope	Moraine and till.			do	do	Do.
New Lexington	Till			Richmond and Maysville.	Richmond and Maysville.	Small.
New Paris	Moraine	25	Plenty	"Niagara"	"Niagara"	Plenty.
Sugar Valley	do			do	do	Do.
West Alexandria.	do	Deep	Plenty	Richmond and Maysville.	Richmond and Maysville.	Small.
West Elkton	Till and Moraine.	10	Moderate.	"Clinton" (?)	"Clinton"(?)	Plenty.
West Florence	Moraine			"Niagara"	"Niagara"	Do.
West Manchester.	Till	−80 ?	Plenty	do	do	Do.
West Sonora	Till and Moraine.	+40	do	do	do	Do.
Winchester (Gratis post office).	Till	10	Moderate.	Richmond and Maysville.	Richmond and Maysville.	Small.

WARREN COUNTY.

By M. L. Fuller.

SURFACE FEATURES.

Warren County is essentially a plateau, standing for the most part 800 to 900 feet above sea level but rising at some points to 1,000

feet or over. The plateau is divided into eastern and western parts by the deep valley of the Little Miami, the bottom of which is 200 feet or more below the upland surface. The plateau is also cut at the extreme northwest corner by the valleys of the Miami and the numerous tributaries to the two rivers, as well as by certain other valleys not now occupied by streams of any size. The uplands are much less cut by ravines than those in counties nearer the Ohio, the plateau surface being flat or gently rolling throughout the greater part of its extent. Among the valleys formed by streams other than those now occupying them may be mentioned that extending from the Miami near Middletown southeastward to the Little Miami at Deerfield and that leaving the Little Miami near Freeport and passing southwestward past Lebanon and thence southward to the main valley at Deerfield. These appear to have been drainage channels carrying glacial waters set free by the melting of the ice sheet when it occupied the region a short distance to the north (Pl. II, p. 24).

Other surface features of importance are the morainal hills, the most pronounced belt of which crosses the county from the northeast to the southwest corner, passing Lebanon. Another belt starts near Little Miami River at Waynesville and extends southeastward into Clinton County. These hills are best developed in the valleys, where they have an elevation of 50 to 100 feet above the surrounding bottoms. On the uplands they are far less conspicuous, few of them being over 20 feet in height.

WATER-BEARING FORMATIONS.

The water-bearing beds of Warren County include, among the surface deposits, alluvium, till, and moraines, and among the rock formations the "Niagara," "Clinton," Richmond, and Maysville formations.

SURFACE DEPOSITS.

ALLUVIUM.

The alluvial deposits in Warren County are extensive, occurring in the valleys of both the present streams and the old glacial streams. Of the recent deposits those of Miami and Little Miami Rivers are the most extensive, the alluvial plain of the former having a width of 2 miles or more in places and that of the latter a width of one-half to three-fourths of a mile. Considerable alluvium is also found in the valleys of Todds Fork and some of the minor streams. The deposits of glacial alluvium of the two valleys mentioned in the preceding section also reach a considerable width, especially in the valley connecting the Miami and Little Miami.

The alluvium of the Little Miami is prevailingly sandy or gravelly even near the surface, doubtless owing to considerable velocity of the waters during the excavation of the narrow gorge. In the valley of the Miami the alluvium includes more silt, especially in its upper portion, many wells having to be sunk 40 feet or more to procure supplies. Some till appears either to be included with or to underlie the older deposits of Miami River and also those in the two glacial valleys mentioned.

The sandy and gravelly alluvium of the Little Miami and of some of the other streams is in places very extensive and affords abundant water to wells from 40 to 60 feet in depth. On the Miami, also, water is obtained in abundance, although some silt is present and wells are not so uniformly successful, at least at shallow depths, as on the Little Miami. The same is true to a still greater extent in the old valley connecting the two streams and in the Lebanon cut-off of the Little Miami.

LOESS.

South of a line stretching from the northeastern to the southwestern corner of the county the surface drift is much older than in the deposits to the north, belonging to an earlier glacial stage. This older drift is covered throughout by a thin sheet, ranging from a few inches to several feet in thickness, of a bluish or brownish loamy silt known as loess. Owing to its thinness it is of no importance as a water-bearing formation in Warren County, but it assists in collecting the rainfall and in feeding water to the underlying till and rock.

TILL.

The pebbly clay or till varies in color from yellowish or brownish near the surface to blue or gray at depths of 5 or 10 feet or more. It contains many small pebbles and a few bowlders. Its thickness is usually under 25 feet and in some places under 10 feet, but it seems to be considerably thicker at points near the eastern border of the county, possibly reaching 100 feet or more in the vicinity of Todds Fork. Here and there, even on the plateau, the rock is almost at the surface, some wells encountering it at less than 10 feet.

The thin till is of little importance as a water-bearing formation, but that from 15 to 25 feet thick absorbs considerable quantities, which it supplies to shallow dug wells. The till is also important in absorbing and retaining water falling upon the surface and feeding it to the underlying rocks.

MORAINAL DEPOSITS.

The morainal deposits, which lie in a belt stretching from the northeast to the southwest corner of the county, reach their greatest development in the valleys, in some of which they have a thickness

of 100 feet. Where conspicuously developed the moraines seem to be composed largely of sand and gravel, from which the water rapidly drains away to the near-by valleys or sinks to the underlying formations. For this reason wells almost never obtain supplies in the gravelly moraines, at least not until a depth equivalent to that of the general water level in the vicinity is reached. However, where the till is mixed with the gravel the downward passage of the water may be obstructed and accumulations take place in irregularities of its surface. Some wells sunk at such points procure water, but the supplies are generally uncertain.

ROCK FORMATIONS.

"NIAGARA" LIMESTONE.

Very little "Niagara" limestone is found in Warren County, the total thickness exposed being not over 50 feet and the area only a few square miles even where it is most extensively developed in the region northeast of Springboro, not far from the north line of the county. The lower part of the formation is a bedded limestone suitable for building (Dayton limestone) but only a few feet thick. Above this comes a bed of shale, which is in turn overlain by limestone making up the remainder of the 50 feet.

The "Niagara" limestone is found in so small an area that it is unimportant as a water-bearing formation in Warren County, although it contains considerable water and yields moderate supplies to the open wells that penetrate it.

"CLINTON" LIMESTONE.

In Warren County the "Clinton" limestone is only 15 or 20 feet thick and consists of a lower calcareous sand and an upper pinkish semicrystalline limestone. It underlies the "Niagara" in the hilltops northeast of Springboro and caps small hills a few miles north of Todds Fork on the eastern line of the county. Southeast of Freeport about three-fourths of an acre of "Clinton" overlies the drift, appearing to have been moved from its original position.

The "Clinton" outcrops, except that northeast of Springboro, are too small to contain much water and are so deeply covered by drift as to be unavailable. It is probable that northeast of Springboro, however, the formation carries considerable water which it yields to wells penetrating it. Some springs occur near its base, but, owing to the scanty outcrops of the formation, these are of little importance.

RICHMOND AND MAYSVILLE FORMATIONS.

The Richmond and Maysville formations consist of a shaly layer several feet in thickness at the top and alterations of thin limestone and shale in the remaining portion. About 400 feet of the formations is exposed in the county, and this seems to be nearly their en-

tire thickness, for the underlying Eden shale appears beneath them not far from the south line of the county. The two formations underlie the entire county, except for the small patches of "Niagara" and "Clinton" described above.

Where either the alluvium or the "Clinton" limestone is available it constitutes the principal source of supply, but elsewhere in the county shallow wells are obliged to rely mainly on the Richmond and Maysville formations. Owing to the covering of drift, which serves as a feeder to these formations, moderate amounts of water are concentrated in their upper weathered portion and furnish fair supplies to open wells. Few drilled wells get water from the Richmond and Maysville formations in Warren County.

NOTES BY TOWNS.

FRANKLIN.[1]

In the central and northern parts of Franklin an abundance of water can usually be obtained from gravel beds in the alluvium at depths of 20 to 175 feet, the largest supplies generally being found at 60 and 80 feet. At the south end of the town the alluvium valley filling is apparently much thinner, wells soon reaching a till or clay in which there is little water, or entering dry rock. Most wells in this part of town have been failures.

The wells from which Franklin originally obtained its supply were located in the vicinity of the Franklin Mills, near the side of the valley, but later the mill wells withdrew so much water that the supply became insufficient and new wells were sunk by the town near the river on the opposite side from the town. These wells are a little more than 60 feet in depth, are so situated as to be free from all danger of pollution, and appear to yield enough for all ordinary demands. Further particulars are given on page 52.

KINGS MILLS.[1]

Kings Mills consists of the works of the Peters Cartridge Co. and the K. P. Co., located in the valley of the Little Miami, and of a small but neat and well-kept town on the plateau above. The residents of the older part of the village mainly use dug wells 20 to 40 feet in depth, sunk through blue clay or till to the top of the rock. In the newer part of town drilled wells have been substituted because they can be sunk more quickly and cheaply and are much safer. They are said to go down to the rock, which they reach at depths similar to those in the old part of town. One well was drilled to 160 feet, and several to depths of 50 or 60 feet, but generally without material increase of supply. In some the water found in the upper part was lost through "gravel" (crevices?) farther down. An analysis of the water from the well at the Homestead Hotel is given

[1] Conditions in 1906.

on pages 206–207. In the valley several large springs occur, one of them yielding, it is estimated, nearly 35,000 gallons daily.

The town has a public supply for extinguishing fires, the water being taken from the river.

LEBANON.[1]

Two wells were sunk at Lebanon during the oil and gas boom in 1887. The first, which reached a depth of 1,300 feet, obtained large quantities of salt water near the bottom, but no oil nor gas in paying quantities. Chalybeate water was encountered in the drift gravels. The second well, sunk in the valley of Turtle Creek, gave the following record:

Record of deep well at Lebanon.

	Thickness.	Depth.
	Feet.	*Feet.*
Drift: Mainly gravel and sand	256	256
Maysville formation: Blue limestone and shale	244	500
Eden shale and Point Pleasant formation: Dark shale and limestone	162	662
"Birdseye" limestone: Hard white limestone	38	700

A public supply was installed by Lebanon in 1896, the water being obtained from a number of wells driven from 96 to 104 feet through alernations of clay, sand, and gravel on low ground near a small tributary of Turtle Creek. The water flows feebly at the surface, and is siphoned to a receiving well, from which it is pumped to the standpipe. Other information concerning the supply will be found on page 52. It appears to be safe and suitable for all domestic uses. A partial analysis will be found on pages 206–207.

MASON.[1]

Two deep wells, the second completed late in 1906, have been drilled for oil and gas at Mason. The first, sunk a quarter of a mile north of town, had approximately the following record:

Record of deep well at Mason.

	Thickness.	Depth.
	Feet.	*Feet.*
Drift:		
Clay, till, and quicksand	100	100
Blue clay	10	110
Richmond, Maysville, and Eden formations: Alternating layers of bluish limestone and shale	555	665
Point Pleasant formation: Dark shales and limestone	155	720
"Birdseye" limestone:		
Limestone	50	770
Blue mud	2	772

The record of the second well was substantially the same as that of the first. Some strong pockets of gas were encountered, but they

[1] Conditions in 1906.

soon blew off. A little salt water was obtained in both wells. In the new well, a mile southwest of town, flowing water was obtained from a sandy bed in the till at about 85 feet. An analysis of this water appears on pages 206–207.

MORROW.[1]

Although a town of considerable size, Morrow has no public water supply, doubtless because of the accessibility of Little Miami River in case of fire. Most of the people formerly depended on dug wells, but many of these were filled a few years ago by material washed in during a flood and have been replaced by wells driven in the fillings of the old wells. Many entirely new driven wells have also been sunk and a few drilled wells put down. Owing to the situation of the town at the base of a bluff and the movement of the ground water toward the river there is considerable danger that the shallower wells may become polluted, especially along the edge of the valley. It is believed that wells sunk near the center of the valley at a point above the town would afford a safer and more satisfactory supply than the present shallow wells.

MURDOCK.[1]

A deep well was sunk many years ago for oil and gas in a ravine not far from Murdock. A strong brine, utilized at one time in the manufacture of salt, was obtained, but neither oil nor gas nor any large amount of fresh water was found.

SPRINGBORO.[1]

The spring emerging from the drift near Springboro is of interest as being, according to reports, one of the largest in this part of Ohio. It was formerly used as a source of water power for a flouring mill and woolen factory.

WAYNESVILLE.[1]

The public supply of Waynesville was installed in 1900–1901, the water being obtained from driven wells sunk at the upper edge of the Little Miami flat south of the village. The wells are about 40 feet in depth and penetrated a succession of clays, sands, and gravels, stopping in a gravel resting on top of the underlying rock. The wells are so situated as to be free from pollution and are to be preferred to the private wells, especially the shallow open wells in the limestone and shale. Additional data regarding the supply will be found on page 52.

[1] Conditions in 1906.

WATER PROSPECTS.

The underground-water conditions in the towns and villages of Warren County are indicated in the table below:

Underground water conditions in Warren County.

Town.	Surface deposits.			Rock formations.		
	Material.	Thickness.	Water supply.	Rock nearest surface.	Water-bearing rocks.	Water supply.
		Feet.				
Blackhawk	Till	15	Moderate.	Richmond and Maysville.	Richmond and Maysville.	Small.
Blue Ball	do	15	do	do	do	Do.
Butlerville	do	15	do	do	do	Do.
Camargo	do	15	do	do	do	Do.
Camp Hagerman	Alluvium		Plenty	do	do	Do.
Carlisle	do	65+	do	do	do	Do.
Corwin	do	30+	do	do	do	Do.
Cozzadale	Till	15	Moderate.			
Dodds	do	15	do	do	do	Do.
Edwardsville	do	25	do	do	do	Do.
Fort Ancient	Alluvium		Plenty	do	do	Do.
Foster	Alluvium, talus.		do	do	do	Do.
Franklin	Alluvium	40–120+	Fair	do	do	Do.
Harveysburg	Till, moraine	25	Moderate.	do	do	Do.
Hopkinsville	Till	18	Very small.	do	do	Do.
Kings Mills	do	20	Plenty	do	do	Do.
Lebanon	Till, alluvium	50+	Moderate.	do	do	Do.
Leeland	Moraine, till	25	do	do	do	Do.
Level	Till	20	do	do	do	Do.
Lytle	do	10	Small	"Clinton" (?)	"Clinton" (?)	Usually plenty.
Maineville	Alluvium		Moderate.	Richmond and Maysville.	Richmond and Maysville.	Small.
Mason	Till, moraine	30	do	do	do	Do.
Merrittstown	Till	12	do	do	do	Do.
Middleboro	do	10	Plenty	do	do	Do.
Morrow	Alluvium		do	do	do	Do.
Mount Holly	do		do	do	do	Do.
Murdoch	Till	25	Moderate.	do	do	Do.
Osceola	Alluvium		Plenty	do	do	Do.
Oregonia	do	25+	do	do	do	Do.
Pekin	Till	15	Fair	do	do	Do.
Pleasant Plain	do	16	Plenty	do	do	Do.
Red Lion	do		Moderate.	do	do	Do.
Ridgeville	do	15	do	do	do	Do.
Roachester	do	25	Fair	do	do	Do.
Rossburg	do	15	do	do	do	Do.
Socialville	Moraine, till	20	Moderate.	do	do	Do.
South Lebanon	Alluvium		Plenty	do	do	Do.
Springboro	Till	15	Small	do	do	Do.
Twentymile Stand.	do	10	Fair	do	do	Do.
Union	Till, alluvium	Deep.	Plenty	do	do	Do.
Waynesville	Alluvium		do	do	do	Do.
Wellman	Till	20	do	do	do	Do.
Zoar	do	30	Moderate.	do	do	Do.

CHEMICAL CHARACTER OF THE WATERS OF SOUTHWESTERN OHIO.

By R. B. Dole.

INTRODUCTION.

The purpose of the following discussion is to suggest standards that may assist intelligent study of the analytical data and may show the broad general relations with respect to quality between the wells and other sources of supply in southwestern Ohio and in other regions. The methods of testing the waters are briefly outlined, the chief uses of water reviewed, and the qualities peculiar to waters of each class discussed. In conclusion a brief summary of the general characteristics of the waters of the area is presented. Discussion of individual waters is not attempted, the interest in these being too local to merit space here.

ANALYTICAL RESULTS.

Many analyses quoted in the succeeding pages were made by industrial chemists, chiefly to determine the value of the waters as sources of railroad supply. Such estimates are usually made in accordance with accepted procedures for industrial work and the results are sufficiently accurate for most purposes. These analyses, originally stated in hypothetical combinations in grains per gallon, have been recomputed to ionic form in parts per million in order that they may be compared with other analyses.

The analyses by Dole and Roberts were made in a special laboratory of the United States Geological Survey in accordance with the methods outlined in Water-Supply Paper 236, pages 9 to 26, inclusive. The probable accuracy of the methods and their sources of error are discussed in the same publication. The samples of water for these tests were collected in 1-gallon glass-stoppered bottles supplied to the field force from the laboratories, and the waters were examined as soon as practicable after collection.

Field assays of water by Parker and Evans, reported in the table of analyses, were made in accordance with the methods outlined in

Water-Supply Paper 151, and though only a few estimates were made for each water they furnish some additional information concerning the quality.

The results of the analyses in this paper are stated in parts per million, and though the amounts of water used for examination were measured by volume the mineral content is generally so low that the figures may be considered to represent parts per million by weight. Simplicity of computation, avoidance of fractions, and certainty of the basic unit make this decimal system especially satisfactory for practical purposes. Expression of the results of water analyses in parts per million has been generally adopted by sanitary and research chemists and by many technical chemists, and the exclusive employment of this unit industrially is delayed only by more or less objectionable precedent.

For the convenience of those who may desire to transform the results to other forms of expression it may be stated that multiplying the number of parts per million by 0.058 gives the equivalent in grains per United States gallon of 231 cubic inches; multiplying it by 0.07 gives the equivalent in grains per imperial gallon; and multiplying it by 0.00833 gives the equivalent in pounds per thousand gallons.

The analytical methods commonly employed in examining water permit the estimation of the elements and radicles present, the determination of the total amount of mineral matter in solution, and the more or less approximate separation of the incrusting from the nonincrusting constituents. Further than this, however, ordinary chemical tests give little knowledge regarding the chemical composition of mineral waters, and consequently the exact amounts of the different salts in solution are largely conjectural. Though such salts as sodium chloride, potassium carbonate, and magnesium sulphate are probably present, they are not determined as such, and their exact amounts can not be computed from the analytical data. The ionic form of stating the analyses—that is, stating the radicles present—has been adopted in this report because it gives fact and not opinion. The form is entirely practical and presents the actual results for the consideration and criticism of persons other than those making the tests.

WATERS IN GENERAL.

MINERAL CONSTITUENTS OF WATER.

All natural waters contain dissolved or suspended in them more or less of all materials with which they have come into contact. Such materials are taken up in amounts determined principally by their chemical composition and physical structure, by the temperature, pressure, and duration of contact, and by the condition of substances

that have previously been incorporated in the water. To designate such suspended and dissolved matter as "impurities" is hardly correct, because they are introduced normally—in strict accordance with natural conditions and not necessarily by human agency. It has become customary, however, to call such substances impurities when they are detrimental or injurious in some proposed use of a water supply. For purposes of examination the substances that may be present are classified as suspended matter, such as particles of clay or leaves; dissolved matter, either of mineral or organic origin; microscopic animals or plants; and bacteria. The presence or absence of very small animals and plants likely to affect the quality of waters is determined by microscopic examination, and the chance of contracting disease by drinking the water is ascertained by bacteriological processes. The amount and the nature of the mineral ingredients are usually determined by estimating total suspended matter, total dissolved matter, total hardness, total alkalinity, silica, iron, aluminum, calcium, magnesium, sodium, potassium, carbonates, bicarbonates, sulphates, nitrates, chlorides, free carbonic acid, and free hydrogen sulphide. These estimates measure the materials most commonly present and most likely to affect the value of the waters. Articles describing the methods employed in making these estimates have already been cited (p. 172).

In judging the value of a water from the data afforded by analysis it is necessary to consider the supply both in relation to the use to which it is to be put and in its relation to other available supplies. Besides being used for drinking and for general domestic purposes, water is essential in steam making, paper making, starch manufacture, and many other industrial processes. The medicinal properties of the dissolved minerals are supposed to give many waters special significance. For each of these applications the amounts of certain ingredients in the water determine its value and assist in its classification. For example, considerable iron in a water may be harmful in one industrial process and harmless in another. The value of a water for another process may be directly measurable by the amount of suspended matter, the amount of dissolved matter not being significant. Furthermore, many waters that are considered of great medicinal value are unfit for boiler use.

To catalogue waters as good or bad, hard or soft, pure or impure, is indefinite and may be misleading. Absolutely pure water (H_2O) does not exist in nature, and, as stated before, a water should not be called impure when it contains only substances derived by natural means from natural sources. The arithmetical values of terms ordinarily employed to describe the quality of water, like those of many other words, are variable and largely dependent on local usage. In New England, for instance, water to be considered soft must have

much less than 100 parts per million of total hardness, and water containing 30 or 40 parts of sulphates would not be used. In southwestern Ohio, however, it would be difficult to find a well water with total hardness less than 100 parts per million, yet many well waters in that region are called soft, and many waters containing 30 to 40 parts of sulphates are used in boilers without occasioning much comment. This example illustrates the uncertain significance of general descriptive words in classifying waters and emphasizes the advisability of knowing the intended use of a water and the composition of other available supplies before pronouncing judgment on its quality.

WATER FOR DOMESTIC USE.

PHYSICAL QUALITIES.

Suspended mineral matter clogs pipes, valves, and faucets, and growths of microscopic plants suspended in water commonly cause stains in clothes and bad odors. The red or reddish-brown masses of suspended matter sometimes occurring in well waters of this region are usually growths of *Crenothrix*, which is described by Whipple[1] as a small filamentous plant having a gelatinous sheath colored by a deposit of ferric oxide. It grows especially in ground waters containing considerable iron, forming tufts or layers in water pipes and well casings and sometimes clogging them. Detached particles escaping through faucets give the water an unsightly appearance and cause rusty stains on clothes washed in it. So far as is known, *Crenothrix* in drinking water does not cause disease.

True color in water is usually due to dissolved vegetable matter and causes serious objection among consumers only when it exceeds 20 or 30 parts per million.

In general the well waters of this area are satisfactory in respect to suspended mineral matter and color. In some places finely divided material from quicksands enters driven wells, but such trouble is not nearly so serious as in some other parts of the country. A few of the waters, especially those containing iron, develop a turbidity of 10 to 30 parts per million on exposure to the air, owing to the precipitation of dissolved matter, which gives rise to an apparent though not a real color. Most of the color recorded in analyses of these well waters is due to this cause, and true colors are so low as to be insignificant. Odors may be due to several causes. An odor like that of rotten eggs, encountered in many waters in the oil belt, is due to free hydrogen sulphide (H_2S). Growths of microscopic organisms in tanks and water mains often have unpleasant odors that make the water objectionable. Perfectly acceptable drinking supplies are free from color, odor, taste, and turbidity.

[1] Whipple, G. C., The microscopy of drinking water, New York, 1899, p. 144.

BACTERIOLOGICAL QUALITIES.

Before a water is used for domestic purposes it should be reasonably certain that it is free from disease-bearing organisms, and since present bacteriological technique does not permit positive statement regarding the presence or absence of such organisms, it is advisable to guard supplies against all chances of infection. The disease germs most commonly carried by water are those of typhoid fever. The bacilli enter the supply from some spot infected by the discharges of a person sick with this disease, and, though comparatively short lived in water, they persist in fecal deposits and retain their power of infection for remarkable lengths of time. Consequently, wells should be so located that their waters are guarded against the entrance of filth of any kind, either over the top or by infiltration. Pumps and piping should also be protected. Water from a carefully cased well more than 20 or 30 feet deep is acceptable if the well is located according to reasonable judgment in regard to privies, cesspools, and other sources of pollution. Many open dug wells and many pits constructed as reservoirs around the tops of casings are exposed to fecal contamination from above or through cracks in poorly built side walls. Care should be taken that the casings of deep wells do not become leaky near the surface of the ground so as to allow pollution to enter. As a matter of ordinary precaution the ground should be kept clean and water should not be allowed to become foul or stagnant near any well, no matter how deep. If shallow dug wells are necessary, they should be constructed with water-tight casings extending as far as practicable into the well and also a short distance above ground. The floor, or curbing, should be water-tight and pumps should be used in preference to buckets for raising the water. Every possible precaution should be taken to prevent feet scrapings and similar dirt from getting into the water by way of the top of the well. Underground water is not only less likely to become contaminated if protected from surface washings, air, and light, but it keeps better and is less likely to develop microscopic plants that give it an unpleasant taste.

CHEMICAL QUALITIES.

Amounts of dissolved substances permissible in a domestic supply depend much on their nature. No more than traces of barium, copper, zinc, or lead should be present, because these substances are poisonous. The occurrence of these elements in measurable amounts in ordinary well waters is so rare that tests for them are not usually made. Any constituent present in sufficient amount to be clearly

perceptible to the taste is objectionable. Water containing two parts per million of iron is unpalatable to many people, and even this small amount can cause trouble by discoloring washbowls and tubs and by producing rusty stains on clothes. Tea or coffee can not be made satisfactorily with water containing much iron, because a black, inky compound is formed. Four or five parts of hydrogen sulphide make a water unpleasant to the taste, and this dissolved gas is objectionable also because it corrodes well strainers and other metal fittings. The amounts of silica and aluminum ordinarily present in well waters have no special significance in relation to domestic supply. The alkalies, sodium and potassium, are high in most Ohio waters in which chlorides are high.

Approximately 250 parts of chlorides make a water taste "salty" and less than that amount causes corrosion. In regions where the chloride content runs as low as 5 or 10 parts in normal waters unaffected by animal pollution the amount of chlorides is frequently taken as a measure of contamination. But such practice in southwestern Ohio is out of the question because (1) the normal chloride content in most of the well waters is so high that the small changes possibly caused by animal pollution are insignificant and (2) because wells near together and free from contamination may differ 200 or 300 per cent in their content of chlorides, owing to difference in the composition of the materials from which they draw their respective supplies. Therefore the establishment of isochlors, or lines of equal chlorine, in this area would be of no value whatever to the sanitarian.

Calcium and magnesium are the chief causes of what is known as the hardness of water. This undesirable quality is indicated by increased soap consumption and by deposition on kettles of scale composed almost entirely of calcium, magnesium, carbonates, and sulphates. Calcium and magnesium unite with soap, forming insoluble curdy compounds with no cleansing value and preventing the formation of a lather until all of these two basic radicles has been precipitated. Hardness is measured by the soap-consuming capacity of a water expressed as an equivalent of calcium carbonate ($CaCO_3$), and it can be computed from the amounts of calcium and magnesium in a water or can be determined by actual testing with standard soap solution. The use of soda ash (sodium carbonate) to "break" hard waters or to precipitate the calcium and magnesium is common and effects a saving in the amount of soap. Some large cities in other States have found it advisable to soften their public water supplies instead of leaving that task to the individual consumer.

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WATER FOR BOILER USE.

FORMATION OF SCALE.

The most common trouble caused in boilers by the mineral constituents of natural waters is formation of scale or deposition of mineral matter within the boiler shell. When water is heated under pressure and concentrated by evaporation, as in a steam boiler, certain substances go out of solution and solidify on the flues and crown sheets or within the tubes. These deposits increase fuel consumption, because they are poor conductors of heat, and they also increase the cost of boiler repairs and attendance, because they have to be removed. If the amount of scale is great or if it is allowed to accumulate, the boiler capacity is decreased and disastrous explosions are likely to occur. In two years the inspectors for one insurance company[1] found more than 86,000 boilers, or nearly one-fifth of all those examined, to be defective on account of sediment, incrustation, and scale.

The scale or incrustation consists of the substances that are insoluble in the feed water or become so within the boiler under conditions of ordinary operation. It includes practically all the suspended matter or mud; the silica, probably precipitated as the oxide (SiO_2); the iron and aluminum, appearing in the scale as oxides or hydrated oxides; the calcium, precipitated in the form of carbonate and sulphate; and the magnesium, found in the deposits principally as the oxide but partly as the carbonate. The scale constituted by these substances is therefore a mixture of compounds, which varies in amount, density, hardness, and composition with different conditions of water supply, steam pressure, type of boiler, and other circumstances. Calcium and magnesium are the principal basic substances in the scale, over 90 per cent of which usually is calcium, magnesium, carbonates, and sulphates. If much organic matter is present part of it is precipitated with the mineral scale, as the organic matter is decomposed by heat or by reaction with other substances. If magnesium and sulphates are comparatively low or if suspended matter is comparatively high the scale is soft and bulky and may be in the form of sludge that can be blown or washed from the boiler. On the other hand, a clear water relatively high in magnesium and sulphates may produce a hard, compact scale that is nearly as dense as porcelain, clings to the tubes, and offers great resistance to the transmission of heat. Therefore the value of a water for boiler use depends not only on the quantity of scale produced by it, but also on the physical structure of the scale.

[1] The Locomotive (Hartford), new ser., vol. 21, 1900, p. 29; vol. 22, 1901, p. 21.

CORROSION.

Corrosion or "pitting" is caused chiefly by the solvent action of acids on the iron of the boiler. Free acids capable of dissolving iron occur in some natural waters, especially in the drainage from coal mines, which usually contains free sulphuric acid, and also in some factory wastes draining into streams. Many ground waters contain free hydrogen sulphide, a gas that readily attacks boilers; dissolved oxygen and free carbon dioxide also are corrosive. Organic matter is probably a source of acids, for it is well known that waters high in organic matter and low in calcium and magnesium are corrosive, though the exact nature and action of the organic bodies are not understood. Acids freed in the boiler by the deposition of basic radicles as hydrates are the most important cause of corrosive action. Iron, aluminum, and magnesium are precipitated as hydrates that are later partly or completely converted into oxides. According to the chemical composition of the water the acid radicles that were in equilibrium with these bases may pass into equilibrium with other bases, displacing equivalent proportions of weaker acids, or they may decompose carbonates that have been precipitated as scale, or they may combine with the iron of the boiler shell, thus causing corrosion; or they may do all these. If these acids exceed the amount required to decompose the carbonate and bicarbonate radicles present the iron of the boiler is attacked and the results are pits or tuberculations of the interior surface, leaks, particularly around rivets, and consequent deterioration of the boiler.

FOAMING.

Foaming is the formation of masses of bubbles on the surface of the water in the boiler and in the steam space above the water, and it is intimately connected with priming, which is the passage from the boiler of water mixed with steam. Foaming results when anything prevents the free escape of steam from the water. It may be due to particles of suspended matter, but the principal cause is usually an excess of dissolved substances that increases the surface tension of the liquid and thereby reduces the readiness with which the steam bubbles break. Therefore the tendency of a water to foam varies inversely with the concentration it will undergo before developing an excessive surface tension. As the sodium and potassium salts remain dissolved in the boiler water while the greater portion of the other substances is precipitated, the foaming tendency is commonly measured by the degree of concentration of the alkaline salts in solution, because this figure, considered in connection with the type of boiler, determines the length of time that a boiler may run without danger of foaming.

REMEDIES FOR BOILER TROUBLES.

The best remedy for troubles caused by substances in feed waters is treatment of supplies before they enter boilers. (See p. 195.) When such treatment can not be given there are various ways of reducing potential injury. Low-pressure, large-flue boilers are used with hard waters in many stationary plants in the central States and it is said that the scale formed in them is softer and more flocculent and can therefore be more readily removed than that in high-pressure boilers. Blowing off is about the only practical means of preventing foaming, because this trouble is due principally to concentration of soluble salts in the residual water of the boilers. Accumulated sludge, or soft scale, can be removed by blowing, particularly in locomotive practice. In condensing systems much of the trouble due to mineral matter in the feed water is obviated because the quantity of raw water supplied is proportionately small. The problem is not completely solved in such systems, because the incrusting or corrosive action is transferred from the boiler to the condenser, which requires more or less cleaning and repairing in proportion to the undesirable qualities of the water supply.

BOILER COMPOUNDS.

Boiler compounds are widely used in regions where hard waters abound, but treatment within the boiler should be given only when it is impossible to purify the supply before it enters the boiler. If previous purification is not practicable many feed waters can be improved by judicious addition of chemicals. Many substances, ranging from flour, oatmeal, and sliced potatoes to barium and chromium salts, have been recommended for such use, but only two or three have proved to be truly economical. Cary[1] has classified these substances according to their action within the boiler. Those that attack chemically the scaling and corroding constituents precipitate the incrusting matter and neutralize the acids. Soda ash, the commercial form of sodium carbonate, containing about 95 per cent Na_2CO_3, is the most valuable substance of this character, because it is cheap and its use is attended with the least objectionable results. Tannin and tannin compounds are also used for the same purpose. Palmer[2] mentions the use of limewater to prevent corrosion and to obviate foaming, and it is probable that waters high in organic matter and very low in incrustants would be improved by such treatment. When soda ash is used it neutralizes free acids and prevents

[1] Cary, A. A., The use of boiler compounds: Am. Machinist, vol. 22, pt. 2, 1899, p. 1153.

[2] Palmer, Chase, Quality of the underground waters in the Blue Grass region of Kentucky; Water-Supply Paper U. S. Geol. Survey No. 233, 1909, p. 187.

the precipitation of calcium sulphate by causing the precipitation of calcium carbonate. At the same time the sodium content of the feed is increased in proportion to the amount of soda ash added. The proper amount to be used depends on the chemical composition of each water and the style of the boiler. Cary's second class of boiler compounds comprises those that act mechanically on the precipitated crystals of scale-making matter soon after they are formed, surrounding them and robbing them of their cement-like action. Glutinous, starchy, and oily substances belong to this class, but they are not now used to any considerable extent, because they thicken and foul the water more than they prevent the formation of hard scale. The third class comprises compounds that act mechanically, like those of the second class, and also partly dissolve deposited scale, thus loosening it and aiding in its ready removal. Kerosene is the most effective of such materials.

Many boiler compounds possessing or supposed to possess one or more of the functions just described are on the market, and are widely sold. Some are effective and some are positively injurious. Most of them depend for their chief action on soda ash, petroleum, or a vegetable extract, but all are costly compared with lime and soda ash. It can readily be understood that boiler compounds can not in any manner reduce the total amount of scale, but may increase it. Their only legitimate functions are to prevent deposition of hard scale and to remove accumulations of scale that have become attached to the boiler. Every engineer should bear in mind that a steam boiler is an expensive piece of apparatus and that fuel and boiler repairs also are expensive. Therefore he should hesitate to add substances to his feed water without competent advice regarding their effect. It is far more economical to have the water supply analyzed and to treat it effectively by well-known chemicals in proper proportion, either within or without the boiler, than to experiment with compounds of unknown composition.

CLASSIFICATION OF BOILER WATERS.

Stabler[1] in his excellent mathematical discussion of the quality of waters with reference to industrial uses gives several formulas by which waters may be classified. His methods of calculating the amount and the character of scale likely to result from use of a water are given in slightly altered form:

$$A=Sm+Cm+1.3Fe+1.9Al+1.66Mg+2.95Ca.$$

[1] Eng. News, vol. 60, 1908, p. 355; also Water-Supply Paper U. S. Geol. Survey No. 274, 1911, p. 165.

A, Sm, Cm, Fe, Al, Mg, and Ca represent, respectively, the amounts in parts per million of scale, suspended matter, colloidal matter (silica plus oxides of iron and aluminum), iron, aluminum, magnesium, and calcium in the water. In this formula Ca should not exceed $.668CO_3+.328HCO_3+.417SO_4$, in which CO_3, HCO_3, and SO_4 represent, respectively, the amounts in parts per million of the carbonate, bicarbonate, and sulphate radicles in the water. It is uncertain in some waters whether iron and aluminum are in solution or in colloidal state, but in applying these formulas to Ohio ground waters little error is introduced by assuming that Cm equals silica only. If it is desired to compute the scale-forming ingredients of waters whose analyses in this report give no values for silica, iron, or aluminum, Cm may be taken as 20 and Fe and Al as zero without introducing great error. In clear waters Sm would of course be zero; consequently for most Ohio ground waters the amount of scale may be estimated practically from the figures representing silica, calcium, and magnesium.

In the following Stabler formula B represents the amount of hard scale in parts per million; SiO_2, Mg, Cl, So_4, Na, and K represent the respective amounts in parts per million of silica, magnesium, chlorides, sulphates, sodium, and potassium. If the alkalies are not separated, the figure representing sodium and postassium together and computed as sodium may be used with the Na coefficient in place of the last two terms of these formulas.

$B=SiO_2+1.66Mg+1.92Cl+1.42SO_4-2.95Na-1.74K.$

The ratio between the amount of hard scale and the total amount of scale is an index of the probable hardness of the scale; if the computed quantity of hard scale constitutes one-half or more of the total scale the scale may be considered hard; if the hard scale is less than one-fourth of the total the scale would be soft; and if B divided by A is between one-fourth and one-half, the scale may be classified as medium. For other formulas and comments on those quoted the original article should be consulted.

The committee on water service of the American Railway Engineers and Maintenance of Way Association have offered a classification of waters in their raw state that may be employed for approximate purposes, but, as the report states, "it is difficult to define by analysis sharply the line between good and bad water for steam-making purposes." The following table gives this classification with the amounts transformed to parts per million. In many Ohio waters the total incrusting and corrosive constituents are equivalent approximately to total solids.

Approximate classification of waters for boiler use according to proportion of incrusting, foaming, and corroding constituents.

Incrusting and corroding constituents[a] (parts per million).			Foaming constituents [b] (parts per million).		
More than—	Not more than—	Classification.	More than—	Not more than—	Classification.
.....	90	Good.	.....	150	Good.
90	200	Fair.	150	250	Fair.
200	430	Poor.	250	400	Bad.
430	680	Bad.	400	.....	Very bad.
680	.....	Very bad.			

[a] Proc. Am. Ry. Eng. and Maintenance of Way Assoc., vol. 5, 1904, p. 595.
[b] Idem, vol. 9, 1908, p. 134.

These limits must be interpreted liberally in practice, because they are modified by the comparative hardness of the incrustation and the comparative extent of corrosion effected by waters of the same mineral content but of different chemical composition. Very hard waters may be improved by treatment in softening plants. How bad a water may be used without treatment depends on the cost of artificially softening the water and the amount saved by the use of the softened water. A report[1] of the committee on water service just quoted describes the principles on which such calculations should be based. In general, it is economical in locomotive service to treat waters containing 250 to 850 parts per million of incrustants and those containing less than the lower amount if the scale contains much sulphates.[2] As the incrusting solids may commonly be reduced to 80 or 90 parts per million, the economy of treating boiler waters deserves consideration in a region where most of the supplies contain 300 to 500 parts per million of incrusting and corrosive matter. The amount of mineral matter that makes a water unfit for boiler use depends on the combined effect in boilers of the softening reagents used with such waters and of the constituents not removed by softening. Sodium salts added to remove incrustants or to prevent corrosion increase the foaming tendency, and this increase may be great enough to render a water useless for steaming. It is not of much benefit to soften a water containing more than 850 parts per million of nonincrusting material and much incrusting sulphates.[2] Though waters containing as high as 1,700 parts per million of foaming constituents have been used, it is usually more economical to incur considerable expense in replacing such supplies by better ones.

These numerical standards are only roughly approximate, and they should be interpreted liberally in practice. The value of natural waters for boiler use depends primarily on their corroding and foam-

[1] Proc. Am. Ry. Eng. and Maintenance of Way Assoc., vol. 8, 1907, p. 601.
[2] Idem, vol. 6, 1905, p. 610.

ing tendencies and on the amount and character of scale likely to be deposited by them, but this value should always be considered in connection with local standards, for no matter how low a water may be in undesirable constituents it can not be classed as good if it is poorer in quality than the average water of the region in which it occurs. On the other hand, if the best available supply is poor the economy of purifying it, even at large expense, is obvious.

WATER FOR MISCELLANEOUS INDUSTRIAL USES.

GENERAL REQUISITES.

The manufacture of many articles is affected by the ingredients of natural waters. The quality of water for boiler service has already been discussed; with reference to factories it need only be added that increase of boiler efficiency often justifies purification of poor water when increased value of the manufactured product alone may not be considered to do so. This observation applies particularly to paper, pulp, and strawboard mills, laundries, and other establishments where large quantities of water are evaporated to furnish steam for drying, and to ice factories and similar plants where distilled water is produced. But besides its use for steam making water plays a specific part in many manufacturing processes. In paper mills, strawboard mills, bleacheries, dye works, pickle factories, creameries, slaughterhouses, packing houses, nitroglycerin factories, distilleries, breweries, woolen mills, starch works, sugar works, canneries, glue factories, soap factories, and chemical works water becomes a part of the product or is essential in its manufacture. As the principal function of water in most of these establishments is that of a cleansing agent or a vehicle for other substances, a supply free from color, odor, suspended matter, microscopic organisms, and especially bacteria of fecal origin, and fairly low in dissolved substances, especially iron, is generally satisfactory; but there are some exceptions. Water hygienically acceptable is necessary where it comes into contact with or forms part of food materials, as in the making of beverages and dairy or meat products. As all these ideal conditions are found in but few natural supplies, the manufacturer is confronted with the problems of ascertaining what degree of freedom from these substances is necessary to prevent injury to his machinery or to his output and whether the cost of obtaining such purity is counterbalanced by decreased cost of production and increased value of product.

The effects in some industries of the substances most commonly found in water are here outlined, the object being to offer approximate standards to aid in classification.

FREE ACIDS.

Free mineral acids, such as the sulphuric acid in drainage from coal mines, or the hydrochloric acid in the effluents of some industrial establishments, are especially injurious and nearly always necessitate purification of the water. In paper mills, cotton mills, bleacheries, and dye works acids decompose chemicals and streak the fabrics besides rotting them. They also corrode metal work, rapidly destroying screens, strainers, and pipes. Such effects are likely to follow the use of water that contains a measurable amount of free mineral acid.

SUSPENDED MATTER.

Suspended matter in surface waters may be of vegetable, mineral, or animal origin, as it consists of particles of sewage, bits of leaves, sawdust, sticks, sand, and clay. The silt so common in rivers of the West is largely derived from sand and clay. Few well waters contain suspended animal or vegetable matter, but many carry finely divided sand and clay and many become turbid by precipitation of dissolved ingredients. Suspended matter is objectionable in all processes in which water is used for washing or comes into contact with food materials, because it is likely to stain or spot the product. Suspended matter due to precipitated iron is especially injurious even in small amount on that account. Suspended vegetable or animal matter liable to decomposition or to partial solution is much more objectionable, even in small amounts (10 to 20 parts per million), than are equal quantities of mineral matter. For these reasons water should be freed from suspended matter before being used for laundering, bleaching, wool scouring, paper making, dyeing, starch making, sugar making, brewing, distilling, and similar processes. In making the coarser grades of paper, such as strawboard, a small amount of suspended matter is not especially injurious, but for the finer white and colored varieties clear water is essential.

COLOR.

Color in water is due principally to solution of vegetable matter, and materials bleached, washed, or dyed light shades in colored water are likely to become tinged. Highly colored waters can be used in making wrapping or dark-tinted papers but not the white grades, and paper manufacturers are put to great expense for water purification on that account. The lower waters are in color, therefore, the more desirable they are for use in bleacheries, dye works, paper mills, and other factories where brown tints are undesirable.

IRON.

Iron is the most undesirable dissolved constituent, comparatively small quantities of it necessitating purification. Many ground waters contain 1 to 20 parts per million of iron, which may be precipitated by exposure to the air and by release of hydrostatic pressure, causing the waters to become turbid; many such waters develop growths of *Crenothrix* (see p. 175) that may interfere with industrial operations. In all cleansing processes, especially if soap or alkali is used, precipitated iron is likely to cause rusty or dull spots. In contact with materials containing tannin compounds iron forms greenish or black substances that discolor the product. Therefore many waters containing amounts even as small as 1 or 2 parts per million of iron have to be purified before they can be used industrially. In water for dye works iron is especially objectionable and commonly prevents the use of the water without purification.[1] Iron in the water supply of paper mills may be precipitated on the pulp, giving a brown color, or during sizing or tinting, giving spotty effects. Water containing much iron can not be used in bleaching fabrics, because salts that spot the goods are formed. The dark-colored compounds that iron forms with tannin discolor hides in tanning and barley in malting, and also give beer bad color, odor, and taste.[2]

CALCIUM AND MAGNESIUM.

Calcium and magnesium are similar in their industrial effects. In amount they bear a more or less definite relation to each other, most waters carrying 10 to 50 per cent as much magnesium as calcium. Both are precipitated on whatever is boiled in water containing them, forming a deposit that may interfere with later operations. As they decompose equivalent amounts of many chemicals employed in technical operations they are a cause of waste. Moreover, the alkaline-earth compounds thus formed on fabrics interfere with later treatment. For instance, some of the chemicals used to disintegrate the fibers in making pulp are consumed by the calcium and magnesium in the water supply, though the loss from this source is not nearly so great as that occurring later when the resin soap used in sizing the paper is decomposed by the calcium and magnesium. The insoluble soaps thus created do not fix themselves on the fibers, but form clots and streaks. Similar decomposition of valuable cleansing materials and subsequent deposition of insoluble compounds take place in laundering, wool scouring, and similar processes. In the manufacture of soap calcium and magnesium form with the fatty acids curdy precipitates that are insoluble in water and therefore have no cleansing

[1] Sadtler, S. P., A handbook of industrial organic chemistry, Philadelphia, 1900, p. 483.
[2] De la Coux, M. A. J., L'eau dans l'industrie, Paris, 1900, pp. 187 and 232.

value. Many dyeing operations are interfered with by calcium and magnesium, which neutralize chemicals and change the reaction of the baths besides forming insoluble compounds with many dyes. Highly calcareous waters can not be used for boiling the grain in distilleries because proper action is hindered by the deposition of alkaline-earth salts on the particles of grain, nor for diluting spirits because they cause turbidity.[1] Very soft water, on the other hand, is said to be undesirable in paper mills for loading papers with any form of calcium sulphate, because such waters dissolve part of the loading materials.[2] Probably waters high in chlorides would also be bad for this purpose, because chlorides increase the solubility of calcium sulphate.

CARBONATES.

The effects of carbonates and bicarbonates in waters used in industrial processes are not differentiated in this paragraph. It is not uncommon to estimate the combined carbonic acid and to state it as the carbonate (CO_3) without distinguishing between the carbonate (CO_3) and bicarbonate (HCO_3), though in many natural waters the carbonate radicle is absent and the combined carbonic acid is present in the form of bicarbonates. If hard waters proportionately high in carbonates and low in sulphates are boiled the bicarbonate radicle is decomposed, free carbonic acid is given off, and the greater part of the calcium and magnesium is precipitated. For this reason waters of that character are generally more desirable for industrial operations than waters high in sulphates and low in carbonates, as boiling does not greatly reduce the amount of the hardening constituents under the latter conditions. In beer making waters high in corbonates are said to produce dark-colored beers with a pronounced malt flavor because the carbonates increase the solubility of the nitrogenous bodies, whereas water high in suphates yield pale beers with a definite hop flavor because the sulphates reduce the solubility of the malt and the coloring matters.[3]

SULPHATES.

The influence of sulphates in beer making has been noted. Hard waters with sulphates predominating are desirable in tanning heavy hides because they swell the skins, exposing more surface for the action of the tan liquors.[4] Sulphates interfere with crystallization in sugar making by increasing the amount of sugar retained in the mother liquor.

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[1] De la Coux, M. A. J., op. cit., p. 251.

[2] Cross, C. F., and Bevan, E. J., A textbook of paper making, New York, 1900, p. 294.

[3] Brewing water, its defects and remedies, American Burtonizing Co., New York, 1909, p. 19. Also De la Coux, op. cit., p. 169.

[4] Parker, H. N., and others, The Potomac River basin: Water-Supply Paper U. S. Geol. Survey No. 192, 1907, p. 194.

CHLORIDES.

High chlorides in the waters of southwestern Ohio are usually accompanied by high alkalies. Appreciable amounts of chlorides are injurious in many industrial processes, and this is particularly unfortunate, as no practicable way of removing or reducing this radicle except by distillation has been discovered. Beverages and food products, of course, can not be treated with waters very high in chlorides without becoming salty. In tanning, chlorides cause the hides to become thin and flabby.[1] Animal charcoal used in clarifying sugar is robbed of its bleaching power by absorption of salt, and the quality of sugars is affected by chloride-bearing waters, because saline salts are incorporated in the crystals.[2] In the preparation of alcoholic beverages chlorides in large amount prevent the growth of the yeast and interfere with the germination of the grain.

ORGANIC MATTER.

Organic matter of fecal origin is of course dangerous in any water that comes into contact with food products, and water so polluted should be purified before being used. Care in this respect is particularly necessary in creameries, slaughterhouses, canneries, pickle factories, distilleries, breweries, and sugar factories. Organic matter not necessarily capable of producing disease is undesirable in industrial supplies because it induces decomposition in other organic materials, like cloth, yarn, sugar, starch, meat, or paper, rotting and discoloring them, and because it causes slime spots on fabrics by supporting algæ growths.

HYDROGEN SULPHIDE.

Hydrogen sulphide (H_2S) is a gas with an odor like that of rotten eggs. It occurs dissolved in some underground waters. It is corrosive even in small quantities, and it also injures materials by discoloring and rotting them. It occurs in many waters otherwise unfit for industrial use by reason of their large content of dissolved salts.

MISCELLANEOUS SUBSTANCES.

Silica and aluminum are usually not present in sufficient quantity to have any appreciable effect in industrial processes except when water is evaporated. Large quantities of sodium and potassium, by adding to the amount of dissolved matter, are objectionable in some manufacturing operations. Phosphates, nitrates, and some other

[1] Parker, H. N., loc. cit.
[2] De la Coux, M. A. J., op. cit., p. 152.

substances not noted in this outline interfere with industrial chemical reactions, but they are present in few natural waters in sufficient quantity to have noticeable effect.

WATER FOR MEDICINAL USE.

The relation between the constituents of natural waters and their physiologic action has been discussed at length in the works of Cohen,[1] Crook,[2] and others. To note a few features that are often forgotten or disregarded in considering the application of mineral waters may, however, not be out of place.

The term "mineral" may reasonably be applied to all natural waters, as all contain dissolved mineral matter, but in general practice it is restricted to those that are exploited on account of their supposedly specific physiologic action. The term "medicinal" is sometimes used to distinguish highly mineralized waters from those that are low in mineral constituents and are especially acceptable as table waters by reason of their physical characteristics. The most logical classification of waters for discussing their chemical constituents in relation to therapeutics is that of Peale[3] as modified by Haywood[4] for the ionic form of stating analyses of water, though Haywood's system is somewhat misleading in a few minor details. It is a strictly chemical classification, by which waters are grouped according to their reaction and their predominating basic and acidic radicles, so that the name conveys a statement of the principal active substances.

The therapeutic application of water, or its use for the correction of diseased conditions of the human body, has always been recognized in scientific writings, and the continued and increasing patronage of mineral-spring resorts and the undoubted improvement of many patients treated there clearly indicate that some natural waters have curative properties. Yet the frequent claims of miraculous recovery by the use of mineral waters, together with the extravagant statements regarding the waters, can but rouse skepticism as investigation reveals how meagerly such claims are supported by evidence. Statement of analyses in hypothetical combination adds to the confusion, because the identity and the number of the compounds calculated depend on the judgment of the analyst and not on his laboratory data. Therefore comparison of the analyses of different waters is rendered difficult and misleading. Lithium, for instance, is said to

[1] Cohen, S. S., System of physiologic therapeutics, vol. 9, Philadelphia, 1902.

[2] Crook, J. K., The mineral waters of the United States and their therapeutic uses, 1899.

[3] Peale, A. C., The natural mineral waters of the United States: Fourteenth Ann. Rept. U. S. Geol. Survey, 1894, pt. 2, p. 53; also, The classification of American mineral waters: Trans. Am. Climatological Assoc., May 31, 1907; also, introductory chapter on the classification of mineral waters in Cohen's System of physiologic therapeutics, vol. 9, 1902, p. 299.

[4] Haywood, J. K., and Smith, B. H., Mineral waters of the United States: U. S. Dept. Agr., Bur. Chemistry, Bull. 91, 1905, p. 9.

be a particularly valuable ingredient; yet many analysts report lithium carbonate, sulphate, or chloride in waters, in spite of the fact that possible physiologic action is due to the lithium ion and not to lithium carbonate in distinction from lithium chloride or lithium sulphate; or, in other words, that the action takes place only when the salt is dissociated. If different lithium compounds are reported, it is impossible to measure the effect of the lithium, unless it is recognized that 5.3 parts per million of lithium carbonate, 6.1 parts of lithium chloride, 7.9 of lithium sulphate, and 9.7 of lithium bicarbonate contain each exactly 1 part of lithium. The curative properties of some waters are attributed to minor ingredients that are present in comparatively insignificant quantities, and many waters containing much less than 1 part per million of lithium are widely advertised as lithia waters. Though it is true that many drugs are as efficient when given in very small but frequent doses as when given in one large dose, the therapeutic value of 1 part per million of lithium may well be questioned, for 200 tumblerfuls of the water contain only one ordinary minimum dose of lithium. The physiologic effect of these minor ingredients is usually overshadowed by that of other substances present in much larger quantities. Many strong brines, for example, contain considerable amounts of lithium, but, as Hessler states,[1] the effect of 10 parts of lithium in the presence of 1,000 or more parts of chlorides would probably be insignificant as compared with the effect of the saline constituents. Many mineral springs are found to possess radioactivity, and this characteristic has been advanced as explaining their curative qualities. So far as the writer is informed, however, no acceptable proof of this theory has been offered. On the other hand, the beneficial effect on the human body of water itself, both hot and cold, used internally or externally, is thoroughly recognized in therapeutics, and the curative qualities of waters not containing appreciable amounts of physiologically active substances may be attributed as reasonably to the action of water itself, combined with a normal regimen of diet, exercise, and other hygienic restrictions, as to some mysterious quality or substance yet undiscovered.

PURIFICATION OF WATER.

GENERAL REQUIREMENTS AND METHODS OF PURIFICATION.

Purification of water is removal or reduction in amount of substances that render waters in their raw state unsuitable for use. It is practiced on a large scale with one or more of three objects in view: First, to render the supply safe and unobjectionable for drinking; second, to reduce the amount of the mineral ingredients injurious to boilers; third, to remove substances injurious to machinery

[1] Hessler, Robert, The mineral waters of Indiana, with indications for their therapeutic application: Trans. Indiana State Med. Soc., 1902.

or to industrial products. The largest purification plants in this country have been constructed almost solely for the purpose of producing potable waters, and some waters need no further treatment before being suitable for steaming and for general industrial purposes. But many other waters are hard, and increased appreciation of the value of good water has resulted in demand for the removal of the hardening constituents also. An excellent example of the result of such insistence is the recently installed plant at New Orleans, where hard, colored, turbid, sewage-polluted river water is brought up to practically all industrial and domestic standards of purity.

Removal of bacteria, especially those causing disease, and removal of turbidity, odor, taste, and iron are the principal requirements in purification of a municipal supply, elimination of bacteria and suspended matter being the most important. The common methods of effecting such purification are slow filtration through sand and rapid filtration after coagulation, both methods usually being combined with sedimentation. The first process is known as slow sand filtration and the second as mechanical filtration. The efficiency of such filters is measured primarily by the ratio between the number of bacteria in the applied water and the number in the effluent. This figure, stated in percentage of removal, should be as high as 98, and it often reaches 99.8 per cent under normal conditions with a carefully operated filter of either kind.

Removal of scale-forming and neutralization of corrosive constituents are the chief aims in preparing water for steam making. For this two general methods are employed, namely, cold chemical precipitation followed by sedimentation, and heating with or without chemicals, usually followed by rapid filtration. The first process is carried on in cold-water softening plants and the second in feed-water heaters.

The requirements of the water supplies for industries are so varied that classification of purification methods is difficult. Water properly prepared for domestic and boiler use is suitable for most industrial establishments, and it is more economical for small manufacturers in large cities to buy such water from water companies than to maintain private supplies and purification apparatus. It is usually cheaper, however, for large factories to be supplied from separate sources, not only because of saving in actual cost of water but also because of the opportunity thus afforded of procuring water specially adapted to the needs of the factory. The common methods of industrial-water purification are those already mentioned or combinations of them modified to meet particular needs. In a few industrial processes, notably the manufacture of ice by the can system, water practically free from all dissolved and suspended substances is necessary and distilled water must be manufactured.

Distillation is expensive, though the employment of multiple-effect evaporators has greatly reduced the cost of operation.

Besides the four common systems of purification many minor processes are used, sometimes alone, but more frequently as adjuncts to filters or softeners. Surface waters may be screened through wooden or iron grids or through revolving wire screens to remove sticks and leaves before other treatment. Coarse suspended matter can be removed by rapid filtration through ground quartz or similar material, in units of convenient size, provided with arrangements for washing the filtering medium similar to those used in mechanical filters. Very turbid river waters may be first allowed to stand in large sedimentation basins to reduce the cost of operating the filters by preliminary removal of part of the suspended solids. Supplies undesirable only because of their iron content are aerated by being sprayed into the air or by being allowed to trickle over rocks or by other methods that cause evaporation of carbonic acid and absorption of oxygen, thus precipitating and oxidizing the iron solution so that it can be readily removed by rapid filtration. Similar aeration is often employed to evaporate and oxidize dissolved gases that cause objectionable tastes and odors.

Disinfection by ozone, copper sulphate, calcium hypochlorite, and many other substances kills organisms that may cause disease or may impart bad odors and tastes. Purification of this character must be done with substances that destroy the objectionable organisms without making the water poisonous to animals. Such treatment is especially adapted for sewage-polluted waters,[1] and it is now widely practiced either as an adjunct to filtration of municipal supplies or as an emergency precaution where otherwise untreated supplies are believed to be contaminated. Natural purification of water is accomplished largely through the biological processes mentioned by Hazen,[2] in which the organic matter is oxidized by serving as food for bacteria and objectionable organisms are destroyed by producing conditions unfavorable to their existence. Action of this kind takes place in reservoirs and lakes, and it is also relied upon in many processes for the artificial purification of sewage.[3]

SLOW SAND FILTRATION.

Slow sand filtration consists in causing the water to pass downward through a layer of sand of such thickness and fineness that the requisite removal of suspended substances is accomplished. The slow sand filter is also called the "continuous" and the "English" filter. On the bottom of a water-tight basin, commonly constructed

[1] Phelps, E. B., The disinfection of sewage and sewage-filter effluents: Water-Supply Paper U. S. Geol. Survey No. 229, 1909.

[2] Hazen, Allen, Clean water and how to get it, New York, 1909, p. 83.

[3] Winslow, C.-E. A., and Phelps, E. B., Investigations on the purification of Boston sewage, with a history of the sewage-disposal problem: Water-Supply Paper U. S. Geol. Survey No. 185, 1906.

of concrete, perforated tiles or pipes laid in the form of a grid are covered with a foot of gravel graded in size from bottom to top, and a layer of fine sand 3 to 4 feet in depth is put over the gravel, which serves only to support the sand. When water is applied on the surface it passes through the sand and the gravel, and flows away through the underdrain. The suspended materials including bacteria are removed by the sand, the action of which is rendered more efficient by the rapid formation of a mat of finely divided sediment on the surface. When this film has become so thick that filtration is unduly retarded the water is allowed to subside below the surface and about half an inch of sand is removed, after which filtration is resumed. The sand thus taken off is washed to free it from the collected impurities and is replaced on the beds after they have been reduced by successive scrapings to a thickness of about 20 inches. As cleaning necessitates temporary withdrawal of filters from service, they are divided into units of convenient size, usually half an acre each, so that the operation of the system may not be interrupted. Filters may be roofed and sodded; this facilitates cleaning by preventing the formation of ice, permits work on the filter beds in all kinds of weather, and inhibits algæ growths.

The foregoing are the essential features of a slow sand filter, but several adjuncts render this system more efficient. A clear-water basin for the filtered supply, covered to prevent deterioration of the water, is provided in order that the varying rate of consumption may not affect the rate of filtration. Clarification of turbid water is rendered more economical by allowing it to stand for one to three days, during which a large portion of the suspended matter is deposited, thus lengthening the time between sand scrapings. Another form of pretreatment is passage through roughing or preliminary filters consisting of beds of slag, sponge, or stone, through which the water flows at fifteen to twenty times the rate in sand filters, a very large proportion of the suspended matter being thus removed. Objectionable odors and tastes may be obviated by aeration before or after filtration. Killing the bacteria before filtration by the use of ozone, chlorine, or other germicides is also practiced.

Slow sand filtration removes practically all the suspended matter and the bacteria. Color is only slightly reduced, and the hardness is not changed. The process is especially adapted to waters low in color, suspended matter, and animal pollution. Very small particles of clay are not removed by these filters, and for waters carrying such particles only for short periods the addition of a coagulant before filtration has been proposed.[1] It can readily be seen that the efficiency of this kind of filter depends largely on the character of

[1] Report of Hering, Fuller, and Hazen on the methods of purifying the water supply of the District of Columbia: Sen. Rept. 2380, 56th Cong., 2d sess.

the sand, as the ability to prevent the passage of suspended matter is governed by the size of the spaces between the sand particles. The rate of filtration depends on the average size of the sand particles, the thickness of the sand bed, the head of water, and the turbidity. Under ordinary conditions of operation in the United States the rate in slow sand filters of water already subjected to sedimentation is 2,000,000 to 4,000,000 gallons per acre per day.

MECHANICAL FILTRATION.

The distinctive features of the mechanical process are the coagulant and the high rate of filtration. The term "mechanical" is applied because of the contrivances for washing the filtering medium; the filter is also known as the American filter. While the raw water is entering the sedimentation basin, which is smaller than that used with slow sand filters, it is treated with a definite proportion of some coagulant, which forms by its decomposition a gelatinous precipitate that unites and incloses the suspended material, including the bacteria, and that absorbs the organic coloring matter. This combined action destroys color and makes suspended particles larger and therefore more readily removable. When aluminum sulphate, the coagulant most commonly used, is decomposed, aluminum hydrate is precipitated and the sulphate radicle remains in solution, replacing an equivalent amount of the carbonate, bicarbonate, or hydroxyl radicle. The natural alkalinity of many waters is sufficient to effect this reaction. One part per million of ordinary aluminum sulphate requires somewhat more than 0.6 part of alkalinity expressed as $CaCO_3$ to insure complete decomposition.[1]. If the alkalinity is not sufficient part of the aluminum sulphate remains in solution and good coagulation does not take place. Therefore lime or soda ash is added if the alkalinity is too low. The proper amount of aluminum sulphate to be used is determined by the amounts of color, organic matter, and suspended matter and by the fineness of the suspended matter, and it is best ascertained by direct experimentation with the water to be purified. Ferrous sulphate instead of aluminum sulphate is sometimes used as a coagulant; lime must always be added with it in order to bring about proper coagulation.

The water, after having been mixed with the coagulant, is allowed to stand three or four hours in the sedimentation basin, where a large proportion of the suspended particles is deposited. It is then passed rapidly through beds of sand or ground stone to remove the rest of the suspended matter. Many filters now in use are built of wood or iron in cylindrical form 10 to 20 feet in diameter, and some are so designed that filtration can be hastened by pressure. The sand, 30 to 50 inches deep, rests on a metallic floor containing perforations large enough to allow ready issue of the water, but small enough to

[1] Hazen, Allen, Report of the filtration commission of the city of Pittsburgh, 1899, p. 57.

prevent passage of sand grains. When the filter has become clogged the flow of water is reversed, filtered water being forced upward through the sand to wash it and to remove the impurities, which pass over the top of the filter with the wasted water. A revolving rake with long prongs projecting downward into the sand mixes it during washing and prevents it from becoming graded into spots of coarse or fine particles. In recently constructed rectangular filters 300 to 1,300 square feet in area compressed air forced through the sand at intervals is used instead of a revolving rake for agitating the sand during washing. The rate of filtration is from 80,000,000 to 180,000,000 gallons per acre per day. The time between washings is 6 to 12 hours, depending principally on the turbidity of the water applied to the filter, and 4 to 8 per cent of the filtered water is consumed in washing.

Mechanical filtration removes practically all suspended matter, reduces the color to an amount that is unobjectionable, and under some conditions removes part of the dissolved iron. The permanent hardness of the water is increased in proportion to the amount of sulphates added as aluminum sulphate, and if only enough lime to decompose the coagulant is added the total hardness is increased. If larger amounts of lime are added, however, the total hardness is reduced. If soda ash is used in place of lime the foaming constituents of the water are slightly increased. As this method of filtration is used almost entirely for river waters with fluctuating contents of suspended and dissolved matter, proper operation requires constant and intelligent attention.

COLD-WATER SOFTENING.

The principal objects of water softening are to remove the substances that cause incrustations in boilers, particularly calcium and magnesium, and to neutralize those that cause corrosion. Chemicals of known strength properly dissolved in water are added to the raw supply in such proportion as to precipitate all the dissolved constituents that can be economically removed by such treatment. The water is then allowed to stand long enough to permit the precipitate to settle, after which the clear effluent is drawn off or the partly cleared effluent may be filtered very rapidly through thin beds of coke, sponge, excelsior, wool, or similar material in order to remove particles that have not subsided in the tanks. The water softeners on the market differ only in the precipitant, in the filtering medium if one is used, and in the mechanism regulating the incorporation of the chemicals with the water. Among the substances proposed as precipitants are sodium carbonate, silicate, hydrate, fluoride, and phosphate, barium carbonate, oxide, and hydrate, and calcium oxide, but of these substances lime and soda ash are almost exclusively used on account of their excellent action and comparative cheapness.

When soda ash (Na_2CO_3) and lime dissolved in water to form a solution of calcium hydrate [$Ca(OH)_2$] are added to a water in proper proportion free acids are neutralized, free carbon dioxide is removed, the bicarbonate radicle is decomposed, and iron, aluminum, and magnesium hydrates and calcium carbonate are precipitated. The four basic substances are removed to the extent of the solubility of these compounds in water; the calcium added as lime also is precipitated, but the sodium from the soda ash remains in solution in the softened water. The precipitate in settling takes down with it a large proportion of the suspended matter. Such treatment with lime and soda ash removes the incrusting constituents. Sodium, potassium, sulphates, and chlorides are left in solution, and the alkalies are increased in proportion to the quantity of soda ash added; that is, the foaming constituents are increased, and this fixes the maximum amount of incrustants that can be treated. The maximum amount of incrustants in a treated water is determined by the solubility of the precipitated substances and by the completeness of the reaction between the added chemicals and the dissolved matter. The sulphate radicle can be removed by using barium compounds, which precipitate barium sulphate, but the poisonous effect of even small amounts of barium is a great objection to its use. The chlorides are not changed in amount by water softening. The chemicals should be very thoroughly mixed with the raw water and sufficient time should be allowed for complete reaction, which proceeds rather slowly, for otherwise precipitation will occur later in pipe lines or in boilers.

FEED-WATER HEATING.

Water heaters are designed primarily to utilize waste heat in stationary boiler plants by raising the temperature of the feed water and thereby lessening the work of the boilers themselves, but they effect also some purification, and many heaters have been specially constructed with that end in view. The heat is derived from exhaust steam or from flue gases; the heaters utilizing steam either are open—that is, operated at atmospheric pressure—or are closed and operated at or near boiler pressure. In accordance with these three conditions, all of which result in distinct purifying effects, feed-water heaters are classified as "open" or "closed" or "economizers," the last named being those using flue gases. Open heaters are best adapted for removing large quantities of scale-forming material. In most forms the steam enters at the bottom and the water at the top, and intimate contact between the two is obtained by spraying the water or by allowing it to trickle over or to splash against plates. In this manner the water is quickly heated nearly to boiling temperature. Dissolved gases are expelled, the bicarbonate radicle is decomposed, and iron, aluminum, part of the magnesium, and calcium equivalent to the carbonates after decomposition of the bicarbonates are precipi-

tated as hydrates, oxides, or carbonates under varying conditions of temperature, pressure, and time. The precipitate agglomerates the particles of suspended matter and makes them more readily removable by sedimentation and filtration. The slowness with which the reactions take place and the presence of acidic radicles other than carbonates to hold the bases in solution prevent complete removal of calcium and magnesium. The addition of soda ash in proper proportion, however, effects fairly complete precipitation of the alkaline earths, and apparatus for constant introduction of this chemical in solution may be provided. After the precipitate has been formed the water passes through filters of burlap, excelsior, straw, hay, wool, coke, or similar materials arranged in units that can be readily cleaned. Open heaters operated without a chemical precipitant remove substances that are soft and bulky and leave in the water the constituents that form hard scale; scale from water treated in such heaters is therefore not so great in amount but is harder than that formed by the raw water.

In closed heaters the water is passed through metal tubes surrounded by steam or around steam pipes, and manholes or other openings are provided for cleaning the scale from the tubes. As the water is heated under pressure some precipitation takes place, but closed heaters are not nearly so efficient in this respect as open heaters, because they do not permit the escape of the gases liberated from the water.

Economizers consist essentially of water tubes set in the flues leading from the furnaces. Facilities are provided for cleaning scale from the inside and soot from the outside of the tubes. As economizers are heated by flue gases, the water in the tubes can be heated under boiler pressure to a much higher temperature than in open or closed heaters, and boiler conditions described in the section on water for boiler use are approximated. The precipitation of incrustants varies greatly with the normally fluctuating temperature of the flue gases.

UNDERGROUND WATERS.

CHEMICAL ANALYSES.

The results of analyses of underground waters in southwestern Ohio are presented in Table 1, which was prepared by M. L. Fuller. The tests by M. L. Fuller, H. N. Parker, and J. R. Evans are field assays made in accordance with the methods described in Water-Supply Paper United States Geological Survey No. 151, and the figures are therefore more or less approximate. The analyses by R. B. Dole and M. G. Roberts were performed in the water-testing laboratory at Washington. The other analyses originally stated in hypothetical combinations in grains per gallon have been recomputed into ionic form in parts per million in order to facilitate comparison of the data.

TABLE 1.—*Chemical composition of*

[Parts per million

Location.	Source.	Owner, etc.	Depth.	Water-bearing formation.	Date of collection.[a]	Analyst.
ADAMS COUNTY.			*Feet.*			
Blue Creek	Well	G. B. Lewis	35	Alluvium	Sept. 22	H. N. Parker
Manchester	do	Hotel Brit	67	do		R. B. Dole and M. G. Roberts.
Mineral Spring No. 2.	Spring	S. R. Grimes		Ohio shale (?)		
Vineyard Hill	Well	Martha McHenry	64	Terrace gravel	Sept 22	H. N. Parker
West Union	do	Samuel Charles	14	"Niagara"	do	do
Do	Spring			do		R. B. Dole and M. G. Roberts.
Winchester	Well	Methodist Church.	25±	Moraine	Sept. 25	H. N. Parker
BROWN COUNTY.						
Browntown	Well	D. O. Dunn	22	Till	Sept. 22	H. N. Parker
Chasetown	do	Burns Bros	55	Richmond and Maysville.	Sept. 7	do
Fayetteville	do	Livery stable	100	do	do	do
Higginsport	do	Schoolhouse	90	Alluvium	Sept. 22	do
Mount Orab	do	Harvey Day	36	Till	Sept. 7	do
New Hope	do	John Young	20	Richmond and Maysville.	Sept. 22	do
Russellville	do	Public well	38	do	Sept. —	R. B. Dole and M. G. Roberts.
Sardinia	do	do	11	Till	Sept. 22	H. N. Parker
Union Plains	do	J. P. Reed	32	do	Sept. 7	do
BUTLER COUNTY.						
Coke Otto	Well	Jno. W. Caldwell	20	Alluvium	Sept. 22	H. N. Parker
College Corner	do	Dr. C. A. Clarke	38	do	do	do
Do	Spring	Tallewanda Spgs				
Darrtown	Well	Ed Phillips	25	Till	Sept. 22	H. N. Parker
Hamilton	do	Becket Paper Co	65–100	Alluvium	Dec. 31	
Do	do	Champion Coated Paper Co.	3,120	St. Peter	Sept. —	R. B. Dole and M. G. Roberts.
Do	do	Hamilton Otto Coke Co.		Alluvium		Hamilton Otto Coke Co.
Do	3 wells	Niles Tool Works	65	do	Sept. 22	H. N. Parker
Do	Well	Black-Clawson Co.	59	do	Sept. 11	do
Millville	do	Charles Falkenstein.	24	do	do	do
Do	do	John Lody	25	Richmond and Maysville.	do	do
Do	do	Peter Swope	42	Alluvium	do	do
Do	do	William Titus	12	do	do	do
Monroe	do	J. F. Constiner	85	Richmond and Maysville.	Aug. 12	M. L. Fuller
New London	do	Morgan Howells	14	Till(?)	Sept. 22	H. N. Parker
Oxford	Spring	W. A. Gawne		Richmond and Maysville.	do	do
Do	Wells	City supply			1903	J. W. Ellms
Do	do	do			1904	do
Do	do	Town of Oxford	22–60	Alluvium	Sept. 22	H. N. Parker
Sevenmile	Well	A. Houser	48	do	do	do
Symmes Corner	do	J. C. Hoovenden	17	Richmond and Maysville.	do	do
Trenton	do		18	Alluvium	Aug. 30	J. R. Evans
CLARK COUNTY.						
Donnelsville	Well		41	"Niagara"	Aug. 17	J. R. Evans.
Eagle City	do	Grist mill	22	Alluvium	Sept. 7	H. N. Parker
Lawrenceville	do		20	Till	do	do
North Hampton	do		36	do	Aug. 17	J. R. Evans.
Pitchin	do	W. B. Kitchen	22	do	Sept. 7	H. N. Parker
Springfield	do	City supply	22	Alluvium	Aug. 20	R. B. Dole and M. G. Roberts.
Do	Spring	Snyder Park		"Niagara"	Sept. 7	H. N. Parker
Do	Well	(2 miles southeast of city).	20	Gravelly till	do	do

[a] Dates are 1906 unless otherwise specified.

[b] Free acid as H_2SO_4, 20 parts.

waters of southwestern Ohio.

unless otherwise stated.]

Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chlorine (Cl).	Total solids.
.....	0.0	.....	.....	.....	.....	.....	121	40	.....	20	.....
14	Tr.	90	19	6.3		14	293	11	16	3.1	309
.....	Tr.	16	22	28	2.1	.0	0	170	.....	12	[b] 250
.....	0	.....	.....	.....	.....	.....	365	35	.....	10	.....
.....	0	.....	.....	.....	.....	.....	265	Tr.	.....	24	.....
19	.3	95	48	18	12	.0	420	49	54	38	537
.....	0	.....	.....	.....	.....	.....	463	108	.....	55	.....
.....	0	.....	.....	.....	.....	.....	365	146	.....	55	.....
.....	.5	.....	.....	.....	.....	.....	348	157	.....	105	.....
.....	2.5	.....	.....	.....	.....	.....	359	Tr.	.....	238	.....
.....	0	.....	.....	.....	.....	.....	308	41	.....	14	.....
.....	0	.....	.....	.....	.....	.....	259	255	.....	100	.....
.....	0	.....	.....	.....	.....	.....	256	70	.....	90	.....
19	.2	135	24	53	6.7	.0	300	102	100	72	667
.....	0	.....	.....	.....	.....	.....	458	201	.....	191	.....
.....	0	.....	.....	.....	.....	.....	324	91	.....	80	.....
.....	0	.....	.....	.....	.....	.....	276	Tr.	.....	10	.....
.....	3	.....	.....	.....	.....	.....	362	Tr.	.....	10	.....
.....	50	64	22	7		.0	196	.....	.....	11	.....
.....	0	.....	.....	.....	.....	.....	306	121	.....	129	.....
6	.....	87	33	.9		.0	350	39	2.5	12	378
22	13	15,900	1,900	34,700	916	.0	10	740	.....	100,440	[c] 138,900
4.4	.....	89	59	31		.0	540	63	.....	16	540
.....	0	.....	.....	.....	.....	.....	362	140	.....	24	.....
.....	0	.....	.....	.....	.....	.....	314	68	.....	20	.....
.....	0	.....	.....	.....	.....	.....	275	47	.....	10	.....
.....	0	.....	.....	.....	.....	.....	314	95	.....	20	.....
.....	0	.....	.....	.....	.....	.....	274	Tr.	.....	24	.....
.....	0	.....	.....	.....	.....	.....	354	56	.....	14	.....
.....	1	.....	.....	.....	.....	.....	486	(d)	.....	528	.....
.....	0	.....	.....	.....	.....	.....	466	362	.....	161	.....
.....	0	.....	.....	.....	.....	.....	362	Tr.	.....	10	.....
.....	.....	79	20	2.4		.0	313	24	.....	3.6	.....
.....	.....	68	24	7.5		.0	300	35	.....	2.1	.....
.....	0	.....	.....	.....	.....	.....	324	43	.....	10	.....
.....	0	.....	.....	.....	.....	.....	282	56	.....	24	.....
.....	0	.....	.....	.....	.....	.....	336	186	.....	29	.....
.....	1	.....	.....	.....	.....	.....	456	256	.....	20	.....
.....	2	.....	.....	.....	.....	.....	396	221	.....	10	.....
.....	0	.....	.....	.....	.....	.....	336	77	.....	20	.....
.....	0	.....	.....	.....	.....	.....	392	116	.....	110	.....
.....	Tr.	.....	.....	.....	.....	.....	414	136	.....	5	.....
.....	0	.....	.....	.....	.....	.....	427	50	.....	20	.....
15	Tr.	88	32	7.2		.0	310	63	8.0	2.4	382
.....	0	.....	.....	.....	.....	.....	398	125	.....	55	.....
.....	0	.....	.....	.....	.....	.....	316	44	.....	14	.....

[c] Specific gravity, 1.110.

[d] More than 850 parts.

TABLE 1.—*Chemical composition of*

Location.	Source.	Owner, etc.	Depth.	Water-bearing formation.	Date of collection.	Analyst.
CLERMONT COUNTY.						
			Feet.			
Amelia	Well		20	Richmond and Maysville.	Sept. 7	H. N. Parker.
Bantam	do	Fair ground	42	do	do	do.
Bethel	do	Town well	26	Till	do	do.
Edenton	do	Public well	20	Alluvium	do	do.
Felicity	do	Town well	30	Richmond and Maysville.	do	do.
Loveland	do		23	Alluvium	Aug. 30	J. R. Evans.
Milford	do	Public well	70	do	Aug. 22	R. B. Dole and M. G. Roberts.
Moscow	do	Town well	70	do	Sept. 22	H. N. Parker.
Neville	do	do	65	do	do	do.
New Richmond	do	(Test well for gas and oil).	1,400	St. Peter	Sept. 7	do.
Do	do		68	Alluvium	Sept. 22	do.
Newtonville	do		28	Richmond and Maysville.	Sept. 7	do.
Tobasco	do		15	do	Aug. 24	R. B. Dole and M. G. Roberts.
West Woodville	do	Public well	20	do	Sept. 7	H. N. Parker.
Williamsburg	do	Curry's livery stable.	26	Till	do	do.
CLINTON COUNTY.						
Blanchester	Well	R. F. Botts	50	Richmond and Maysville.	Sept. 7	H. N. Parker.
Clarksville	do		20	Till	do	do.
Cuba	do	Town well	22	do	do	do.
Midland	do	Dan Hopewell	14	do	do	do.
New Burlington	do	W. S. Huston	36	do	Sept. 11	R. B. Dole and M. G. Roberts.
Do	do[b]	Charles Hartman rolling mill.	36	Richmond and Maysville.	Sept. 20	do.
Do	do[b]	do	36	do	Sept. 11	do.
Oakland	do	Town well	47	Till	Sept. 7	H. N. Parker.
Ogden	do	David Jenks	20	Richmond and Maysville.	do	do.
Wilmington	do	Public supply	172	Till	Aug. 28	R. B. Dole and M. G. Roberts.
DARKE COUNTY.						
New Madison	Well		35		1898	C. B. Dudley.
Do	do		25		1899	do.
Do	do		18		1900	do.
Do	do		16		1898	do.
Do	do		15		1898	do.
Pitsburg	do	J. B. Young	60	"Niagara"	Aug. 17	J. R. Evans.
Woodington	do		14		1893	C. B. Dudley.
Do	do		22		1902	do.
Do	do		20		1902	do.
GREENE COUNTY.						
Bellbrook	Spring	Bellbrook magnetic spring.			(Old)	
Cedarville	Well	Hager Straw-Board & Paper Co.	1,500	"Niagara"		
Clifton	do		14	do	Sept. 7	H. N. Parker.
Jamestown	do	Methodist parsonage.	65	do	do	do.
Do	do	"1776 Mineral Spring."	1,776	St. Peter		
Xenia	do		19		1902	C. B. Dudley.
Do	Spring	City supply	35	Till	Aug. 25	R. B. Dole and M. G. Roberts.
Do	Well		40		1901	C. B. Dudley.
Do	do		138		1901	do.
Yellow Springs	do	Neff Grounds Park		"Niagara"	1901	R. B. Dole and M. G. Roberts.
Do	Well	Public well	70	do	Aug. —	H. N. Parker.
HAMILTON COUNTY						
Blue Ash	Well	Farm well	80	Richmond and Maysville.	Aug. 30	J. R. Evans.

[a] More than 850 parts.

[b] Both samples from same well; see page 95.

waters of southwestern Ohio—Continued.

Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chlorine (Cl).	Total solids.
.....	0	.....	.....	.....	.....	.....	206	229	.....	39	.....
.....	.5	.....	.....	.....	.....	.....	391	124	.....	25	.....
.....	.3	.....	.....	.....	.....	.....	372	313	.....	171	.....
.....	0	.....	.....	.....	.....	.....	451	168	.....	70	.....
.....	0	.....	.....	.....	.....	.....	414	362	.....	373	.....
.....	2	.....	.....	.....	.....	.....	420	146	.....	10	.....
21	.1	87	24	13		.0	342	17	27	7.2	359
.....	0	.....	.....	.....	.....	.....	384	46	.....	10	.....
.....	1	.....	.....	.....	.....	.....	360	185	.....	40	.....
.....	0	.....	.....	.....	.....	.....	414	626	.....	92,920	.....
.....	0	.....	.....	.....	.....	.....	326	47	.....	10	.....
.....	0	.....	.....	.....	.....	.....	330	(*a*)	.....	191	.....
14	.2	179	80	124		.0	427	274	5.0	302	1,203
.....	0	.....	.....	.....	.....	.....	365	229	.....	181	.....
.....	0	.....	.....	.....	.....	.....	398	138	.....	216	.....
.....	0	.....	.....	.....	.....	.....	443	530	.....	20	.....
.....	0	.....	.....	.....	.....	.....	470	66	.....	20	.....
.....	0	.....	.....	.....	.....	.....	266	71	.....	65	.....
.....	0	.....	.....	.....	.....	.....	442	181	.....	105	.....
26	.1	122	35	48	3.5	6.2	333	80	62	102	637
9.0	11	1,100	268	5,750	34	.0	229	9.9	.0	15,000	20,150
14	.3	171	37	144	31	5.8	332	209	60	280	1,132
.....	0	.....	.....	.....	.....	.....	379	56	.....	10	.....
.....	0	.....	.....	.....	.....	.....	443	71	.....	75	.....
19	.3	72	41	9.6		.0	297	48	3.5	6.0	340
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	50	601
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	119	1,057
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	32	615
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	12	650
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	21	502
.....	1	.....	.....	.....	.....	.....	438	56	.....	10	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	6.8	483
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	69	714
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	8.9	542
11	.....	112	36	5.9	8.2	.0	501	25	.....	8.8	459
.....	.....	117		21		.0	392	.....	.....	12	484
.....	0	.....	.....	.....	.....	.....	372	49	.....	30	.....
.....	2.5	.....	.....	.....	.....	.....	470	94	.....	50	.....
69	57	2,351	854	7,951	90	.0	329	2,015	.....	17,110	33,658
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	7.5	445
19	Tr.	77	29	6.1		.0	338	9.9	20	2.2	332
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	19	465
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	7.5	367
24	1.4	89	37	6.9		.0	406	16	.1	2.5	394
.....	Tr.	.....	.....	.....	.....	.0	412	66	.....	151	.....
.....	.....	.....	.....	.....	.....	.....	462	246	.....	270	.....

a Organic and volatile matter 2,431; sulphur (S), 55; hydrogen sulphide (H_2S), 377; thiosulphate radicle (S_2O_3), 18; bromine (Br.) 422; iodine (I), 73; traces of barium (Ba) and phosphates (PO_4); free carbon dioxide (CO_2), 68 parts per million.

TABLE 1.—*Chemical composition of*

Location.	Source.	Owner, etc.	Depth.	Water-bearing formation.	Date of collection.	Analyst.
HAMILTON COUNTY—Continued.			*Feet.*			
Camp Dennison	Well	Well at store	18	Alluvium	Aug. 30	J. R. Evans.
Carthage	Wells	Public supply	135	Glacial gravels	do	do.
Cincinnati	Well	Cincinnati Gas Works.	1,245	St. Peter	(Old)	E. S. Wayne.
Do	do	Sulphosaline spring.	240	"Birdseye"	(Old)	do.
Do	Wells(6)	Clifton Springs Distilling Co.	100	Alluvium (?)	Sept. 22	H. N. Parker.
Do	Wells(2)	do	1,917	St. Peter	do	do.
Do	Well	American Oak LeatherCo.No.1.	180	Point Pleasant	do	H. N. Parker.
Do	do	American Oak LeatherCo.No.2.			do	do.
Do	do	American Oak LeatherCo.No.3.			do	do.
Do	do	Banner Ice Co.	80	Alluvium	do	do.
Do	do	Crystal Springs Ice Co.	150	Point Pleasant	do	do.
Do	do	Foss-Schneider Brewing Co.	85	Alluvium	do	do.
Do	do	do	88	do	do	do.
Do	do	French Brothers Dairy Co.	176	PointPleasant	do	do.
Do	do	Gambrino Stock Co.	284	PointPleasant and "Birdseye."	do	do.
Do	do	do	264	do	do	do.
Do	do	Gibson House well	370?	do	do	do.
Do	do	Grand Hotel	100	Alluvium (?)	do	do.
Do	do	James Heakin Co.	90	do	do	do.
Do	do	Joseph Joseph Bros	180	Point Pleasant	do	do.
Do	do	Jung Brewing Co.	305	Point Pleasant and "Birdseye."	do	do.
Do	do	John Kaufman Brewing Co.	215	Point Pleasant	do	do.
Do	do	Keeling and Bridge	198	do	Sept. 11	do.
Do	do	Kirchmer Construction Co.	90	Alluvium	do	do.
Do	do	A. Lander Packing Co.	180	Point Pleasant	Sept. 22	do.
Do	do	John H. McGowan Co.			do	do.
Do	do	Moerlein Brewing Co.	85	Alluvium	do	do.
Do	do	do	2,408	St. Peter		
Do	do	National Lead Co.	60	Alluvium	Sept. 22	H. N. Parker.
Do	do	Ohio ButterineCo.	68	do	do	do.
Do	do	Palace Hotel	140	do	do	do.
Do	do	Riverside Malting and Elevator Co.	100	do	do	do.
Do	do	Roth & Co.	85	do	do	do.
Do	do	J. Schlachter	90	do	do	do.
Do	do	Standard Marble Works.		do	do	do.
Do	do	Walker Brewing Co.	140	do	do	do.
Do	do	do	100	do	do	do.
Do	do	Crystal Springs Ice Co.	150		1905	Dearborn Chemical Co.
Do	do	Philip Wernsing	15	Alluvium	Sept. 22	H. N. Parker.
Do	do	White Star Laundry.	60	do	do	do.
Do	do	Windisch-Muhlhausen Brewing Co.	170	Point Pleasant.	do	do.
College Hill	do	Cincinnati Northern Traction Co.	35	Till	Sept. 8	do.
Do	do	C. D. and O. C. Peter's Ice Co.	201	Richmond and Maysville.	Sept. —	R. B. Dole and M. G. Roberts.
Do	do	W. T. Simpson	24	do	do	do.
Creedville	do	Fred Schmelch	30	do	Sept. 8	H. N. Parker.
Elmwood	do	Laidlaw-Dunn-Gordon Works.	114	Glacial gravels	Sept. —	R. B. Dole and M. G. Roberts.

[a] Strong odor of hydrogen sulphide.

[b] Iodine (I), 4.7; bromine (Br), 5.8; phosphate radicle (PO_4), 16; organic and volatile matter, 13 parts per million; odor of hydrogen sulphide.

waters of southwestern Ohio—Continued.

Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chlorine (Cl).	Total solids.
.....	.....	.....	.....	.....	.....	.....	384	138	.....	80	.....
.....	Tr.	.....	.....	.....	.....	.....	630	154	.....	30	.....
8.4	4.4	394	120	3,504	29	.0	553	329	.....	5,891	10,567
14	5.2	417	122	3,614	53	.0	630	375	.....	6,042	10,992
.....	1	.....	.....	.....	.....	.....	422	154	.....	218	.....
.....	0	.....	.....	.....	.....	.....	504	[a]460	.....	Much.	.....
.....	5	.....	.....	.....	.....	.....	518	328	.....	238	.....
.....	10	.....	.....	.....	.....	.....	607	287	.....	538	.....
.....	9	.....	.....	.....	.....	.....	780	197	.....	420	.....
.....	6.5	.....	.....	.....	.....	.....	707	383	.....	218	.....
.....	7	.....	.....	.....	.....	.....	479	Tr.	.....	289	.....
.....	2.5	.....	.....	.....	.....	.....	629	406	.....	228	.....
.....	4	.....	.....	.....	.....	.....	679	362	.....	239	.....
.....	15	.....	.....	.....	.....	.....	563	344	.....	319	.....
.....	Tr.	.....	.....	.....	.....	.....	587	Tr.	.....	1,073	.....
.....	.5	.....	.....	.....	.....	.....	468	Tr.	.....	400	.....
.....	10	.....	.....	.....	.....	.....	445	130	.....	218	.....
.....	Tr.	.....	.....	.....	.....	.....	304	138	.....	146	.....
.....	Tr.	.....	.....	.....	.....	.....	397	186	.....	202	.....
.....	11	.....	.....	.....	.....	.....	494	146	.....	60	.....
.....	11	.....	.....	.....	.....	.....	607	300	.....	214	.....
.....	7	.....	.....	.....	.....	.....	521	202	.....	1,022	.....
.....	0	.....	.....	.....	.....	.....	378	Tr.	.....	10	.....
.....	.5	.....	.....	.....	.....	.....	298	Tr.	.....	10	.....
.....	20	.....	.....	.....	.....	.....	630	362	.....	260	.....
.....	0	.....	.....	.....	.....	.....	401	191	.....	308	.....
.....	1	.....	.....	.....	.....	.....	728	383	.....	268	.....
14	5.2	417	121	3,615	53	.0	1,273	375	.....	6,043	[b]10,992
.....	0	.....	.....	.....	.....	.....	554	287	.....	106	.....
.....	2.5	.....	.....	.....	.....	.....	514	287	.....	202	.....
.....	.....	.....	.....	.....	.....	.....	68	46	.....	14	.....
.....	.5	.....	.....	.....	.....	.....	420	103	.....	34	.....
.....	1	.....	.....	.....	.....	.....	467	383	.....	218	.....
.....	6	.....	.....	.....	.....	.....	384	Tr.	.....	20	.....
.....	0	.....	.....	.....	.....	.....	600	287	.....	176	.....
.....	Tr.	.....	.....	.....	.....	.....	504	Tr.	.....	760	.....
.....	0	.....	.....	.....	.....	.....	550	Tr.	.....	380	.....
9.9	.....	109	35	153		.0	467	36	.....	233	[c]820
.....	0	.....	.....	.....	.....	.....	511	276	.....	106	.....
.....	0	.....	.....	.....	.....	.....	504	215	.....	120	.....
.....	1	.....	.....	.....	.....	.....	707	431	.....	242	.....
.....	Tr.	.....	.....	.....	.....	.....	348	Tr.	.....	34	.....
13	53	212	94	303		.0	610	367	.0	702	1,990
27	.05	265	120	37		14	526	678	30	47	1,480
.....	0	.....	.....	.....	.....	.....	451	47	.....	152	.....
26	.2	70	24	8.6		.0	320	18	.5	6.5	293

[c] Organic and volatile matter, 16 parts; oxides of iron and aluminum ($Fe_2O_3 + Al_2O_3$), 20 parts.

TABLE 1.—*Chemical composition of*

Location.	Source.	Owner, etc.	Depth.	Water-bearing formation.	Date of collection.	Analyst.
HAMILTON COUNTY—continued.						
			Feet.			
Harrison	Well	George Dole	100+	Alluvium	Sept. 8	R. B. Dole and M. G. Roberts.
Do	Wells(4)	Harrison Water & Light Co.	40	do	do	do
Do	Well	Town hall	32	do	do	do
Do	do	T. P. Oyler	110	do	Sept. 22	do
Hartwell	do	Store	25	do	Aug. 30	J. R. Evans.
Ivorydale	do	Procter & Gamble		Glacial gravel	1901	J. E. Weber.
Do	do	do		do	1906	do
Ludlow Grove	do	Eikenbrecker salt well.	271		1882	E. S. Wayne.
Madisonville	do	Public supply	150	Glacial gravel	Aug. 30	J. R. Evans.
Mount Washington.	do		30	Old gravels	Aug. 23	R. B. Dole and M. G. Roberts.
Do	do		30	Eden shale(?)	do	do
Norwood	do	Public supply	260	Glacial gravel	Aug. 26	do
Oakley	do		35	do	Aug. 30	J. R. Evans.
Riverside	do	Fleishman Distilling Co.	90	Terrace gravel or alluvium.	Sept. 22	H. N. Parker.
Rossmoyne	do	Store	95	Richmond and Maysville.	Aug. 30	J. R. Evans.
St. Bernard	do	Public supply		Alluvium	do	do
Do	Wells	do			1905	J. W. Ellms.
Valley Junction	Well	Clif. Walker estate.	65	Alluvium	Aug. —	R. B. Dole and M. G. Roberts.
Wyoming	do	Public supply	104–197	do	Aug. 25	do
HIGHLAND COUNTY.						
East Monroe	Well	Town	45	"Niagara"	Sept. 11	H. N. Parker.
Hillsboro	do	City supply	45	Alluvium		R. B. Dole and M. G. Roberts.
Do	Spring	John L. West		"Niagara"	Sept. —	do
Leesburg	Well	Dewey Bros. Co	112	do	Sept. 11	H. N. Parker.
Lynchburg	do	Freiberg & Workum Distillery.	1,534	St. Peter		A. Lasche.
Do	Spring	do			1905	do
Do	do	Town			1905	do
Marshall	Well	W. A. Elliott	18	Till	Sept. 11	H. N. Parker.
Newmarket	do	Town	60	"Niagara"	do	do
New Petersburgh	do	D. R. Cunningham	30	do	do	do
Pricetown	do	J. W. Abraham	42	Till	do	do
MIAMI COUNTY.						
Fletcher	Well		60		1902	C. B. Dudley.
Do	do		24		1900	do
Laura	do	H. H. Coppock	25	Till	Aug. 17	J. R. Evans.
Ludlow	do	H. O. Miles	45	"Niagara"	do	do
Potsdam	do		9	Till	do	do
Rex	do			"Clinton"	Aug. 18	do
1 mile northwest of Rex.	do			Moraine	do	do
Tippecanoe	do	Public supply	55	Alluvium	Aug. 21	R. B. Dole and M. G. Roberts.
5 miles northeast of Tippecanoe.	do			"Clinton"	Aug. 18	J. R. Evans.
West Milton	Spring	Public supply		do	Aug. 22	R. B. Dole and M. G. Roberts.
Do	do				1902	J. W. Ellms.
MONTGOMERY COUNTY.						
Bachman	Well	Mr. Hammel	35	Till	Aug. 15	J. R. Evans.
Brookville	Wells	City		"Niagara"	Aug. 23	R. B. Dole and M. G. Roberts.
Centerville	Well			"Clinton"	Aug. 18	J. R. Evans.
Clayton	do		51	"Niagara"	Aug. 15	do
Dayton	Wells(6)	Ætna Paper Mill	45–48	Alluvium	do	do
Do	Well	Brownell Co	54	do	do	do
Do	do	Davis Sewing Machine Co.		do	1900	A. C. Ehrenfelt.
Do	do	National Cash Register.		do	1906	W. B. Scaife & Sons.
Do	Wells	Public supply	30–60	do	Mar. 7	J. W. Ellms

[a] Less than 5 parts.

waters of southwestern Ohio—Continued.

Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chlorine (Cl).	Total solids.
.....	.8	.....	.....	.....	.....	.....	354	38	.....	10	.....
.....	0	.....	.....	.....	.....	.....	290	35	.....	10	.....
.....	0	.....	.....	.....	.....	.....	336	42	.....	14	.....
.....	0	.....	.....	.....	.....	.....	247	Tr.	.....	10	.....
.....	Tr.	.....	.....	.....	.....	.....	390	136	.....	30	.....
16	.....	102	27	8.1		.0	390	45	.....	12	.....
18	.....	95	27	21		.0	366	44	.....	35	426
21	403	4.936	2.436	29,112		.0	479	73	.....	60,638	98.222
.....	.....	.....	.....	.....	.....	.....	426	35	.....	30	.....
25	.3	128	25	24		.0	459	46	8.0	25	516
16	1.9	80	17	15		.0	270	50	16	13	346
48	.2	72	26	14		.0	348	23	.6	2.2	353
.....	2	.....	.....	.....	.....	.....	408	138	.....	165	.....
.....	Tr.	.....	.....	.....	.....	.....	406	Tr.	.....	20	.....
.....	Tr.	.....	.....	.....	.....	.....	510	344	.....	100	.....
.....	Tr.	.....	.....	.....	.....	.....	672	68	.....	40	.....
.....	.....	101	24	18		.0	406	40	.....	12	.....
17	.1	96	28	10		.0	324	46	31	8.9	388
38	2.2	70	23	13		.0	314	19	.9	10	318
.....	Tr.	.....	.....	.....	.....	.....	334	41	.....	14	.....
18	.2	90	30	7.0		Tr.	366	51	Tr.	2.9	371
16	Tr.	52	32	4.7		7.0	273	2.0	16	1.8	242
.....	0	.....	.....	.....	.....	.....	355	66	.....	20	.....
.....	1.0	86	30	347		.0	329	66	.....	533	1.392
.....	1.2	78	29	2.3	.....	.....	164	41	.....	3.5	390
.....	1.0	79	29	3.5	.....	.....	165	40	.....	5.3	371
.....	0	.....	.....	.....	.....	.....	305	70	.....	55	.....
.....	Tr.	.....	.....	.....	.....	.....	380	Tr.	.....	55	.....
.....	0	.....	.....	.....	.....	.....	443	78	.....	85	.....
.....	0	.....	.....	.....	.....	.....	330	113	.....	24	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.5	493
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	8.9	476
.....	1	.....	.....	.....	.....	.....	544	76	.....	(a)	.....
.....	.....	.....	.....	.....	.....	.....	276	362	.....	40	.....
.....	2	.....	.....	.....	.....	.....	390	186	.....	47	.....
.....	Tr.	.....	.....	.....	.....	.....	461	102	.....	20	.....
.....	2	.....	.....	.....	.....	.....	374	102	.....	10	.....
12	.1	77	27	7.8		.0	313	36	8.0	6.5	342
.....	Tr.	.....	.....	.....	.....	.....	413	53	.....	10	.....
13	.2	60	33	6.3		.0	305	8.4	25	1.3	290
.....	.....	59	40	.....	.....	.....	.....	15	.....	3.0	.....
.....	0	.....	.....	.....	.....	.....	535	176	.....	141	.....
21	.6	84	46	17		.0	343	22	1.0	3.0	420
.....	Tr.	.....	.....	.....	.....	.....	535	208	.....	126	.....
.....	1	.....	.....	.....	.....	.....	389	168	.....	86	.....
.....	4	.....	.....	.....	.....	.....	341	168	.....	25	.....
.....	2	.....	.....	.....	.....	.....	365	116	.....	10	.....
12	.5	110	43	.....	.....	.....	.....	81	.....	13	.....
18	Tr.	148	52	6		.0	459	78	48	38	635
16	.....	52	28	21	.....	.....	270	53	.....	11	.....

TABLE 1.—*Chemical composition of*

Location.	Source.	Owner, etc.	Depth.	Water-bearing formation.	Date of collection.	Analyst.
MONTGOMERY COUNTY—contd.						
			Feet.			
Dodson	Well	Mr. Smith	40	Till	Aug. 15	J. R. Evans.
Englewood	do	W. L. Weyner	50	"Clinton," Richmond, and Maysville.	Aug. 17	do.
Farmersville	do	John Holt	78	Till	Aug. 15	do.
Fort McKinley	do		24	do	do	do.
Kinsey	do	Wm. Kinsey	45	"Clinton"	Aug. 17	do.
Krietzer Corner	do	John Hill	98	Till	Aug. 15	do.
Do	do	Andy Isble	32	do	do	do.
Do	do	W. E. Snyder	35	do	do	do.
Little York	do	G. W. Fair	17	do	Aug. 17	do.
Miamisburg	do	Public supply	60	Alluvium	Aug. 28	R. B. Dole and M. G. Roberts.
Mummaville	do		50	do	Aug. 15	J. R. Evans.
New Germany	do			"Clinton"	do	do.
Do	do		30	do	Aug. 17	do.
Oakridge	do		66	Till	Aug. 18	do.
Phillipsburg	do	School well	18	do	Aug. 17	do.
Pyrmont	do	Mr. Bower	30	do	Aug. 15	do.
St. Richmond	do	Wm. Fairbanks	28	do	do	do.
Sixmile	do	D. Kleppinger	32	do	Aug. 17	do.
Trotwood	Wells	City	60	Alluvium	Aug. 15	do.
Union	Well	T. P. Eby	93	"Clinton," Richmond, and Maysville.	Aug. 18	do.
Wengerlawn	do	Mr. Gray	25	Till	Aug. 15	do.
West Carrollton	do	Public supply	65	Alluvium	Aug. 28	R. B. Dole and M. G. Roberts.
PREBLE COUNTY.						
Camden	Well	Ed Gingerich	130±	Alluvium	Sept. 22	H. N. Parker.
Do	do	Town	31	do	do	do.
Eaton	Wells	Eaton Water-works.	80–85	do	Sept. 25	do.
Do	Well		95		1896	C. B. Dudley.
Do	do	Jonathan Flora	29	Moraine	Sept. 20	R. B. Dole and M. G. Roberts.
Do	do		18		1893	C. B. Dudley.
Do	do	Frank Siebert	34	Moraine	Sept. 25	H. N. Parker.
Do	do		15		1898	C. B. Dudley.
1 mile southeast of Eaton.	Spring			"Niagara"	Sept. 25	H. N. Parker.
Greenbush	Well		28	Richmond and Maysville.	Aug. 12	J. R. Evans.
3 miles southeast of Greenbush.	do		25	do	do	do.
New Paris	do	C. W. Bloom	17	Moraine	Sept. 25	H. N. Parker.
Do	Springs	Cedar Springs		do	(?)	J. N. Hurty.
Do	Spring	Reinheimer Bros.		"Niagara"	Sept. 25	H. N. Parker.
Do	do	do		do	do	do.
Do	Well	Henrietta Wilcox	24	do	do	do.
Verona	do	Store	30	Gravel in till	Aug. 15	J. R. Evans.
West Alexandria	do	S. S. Black	112	Moraine	Sept. 18	R. B. Dole and M. G. Roberts.
West Elkton	do	Elijah Mendenhall	16	do	Sept. 22	H. N. Parker.
Do	do	Town		"Clinton"	do	do.
WARREN COUNTY.						
Butterville	Well	T. H. Starkey	30	Richmond and Maysville.	Sept. 7	H. N. Parker.
Camp Hagerman	do	Valley Packing Co.	66	Alluvium	Aug. 12	
Franklin		Public supply	63	do	Aug. 30	J. R. Evans.
Harveysburg	Well		25	Till	Sept. 7	H. N. Parker.
Kings Mills	do	Homestead Hotel	30	do	Aug. 28	R. B. Dole and M. G. Roberts.
Lebanon	do		20	Alluvium	Sept. 7	H. N. Parker.
Mason	do	Oil well	485	Till	Aug. 29	R. B. Dole and M. G. Roberts.
Morrow	do		22	Alluvium	Sept. 7	H. N. Parker.
Roachester	do		70	Richmond and Maysville.	Aug. 27	do.
Waynesville	do	City supply	40	do	do	do.

[a] Less than 5 parts.

waters of southwestern Ohio—Continued.

Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chlorine (Cl).	Total solids.
.....	Tr.	.....	.....	.....	.....	.....	461	191	.....	80	.....
.....	.....	.....	.....	.....	.....	.....	440	124	.....	30	.....
.....	9	.....	.....	.....	.....	.....	535	64	.....	20	.....
.....	1.5	.....	.....	.....	.....	.....	559	106	.....	86	.....
.....	Tr.	.....	.....	.....	.....	.....	432	106	.....	20	.....
.....	2	.....	.....	.....	.....	.....	240	362	.....	(*a*)	.....
.....	Tr.	.....	.....	.....	.....	.....	461	150	.....	126	.....
.....	Tr.	.....	.....	.....	.....	.....	607	113	.....	(*a*)	.....
.....	Tr.	.....	.....	.....	.....	.....	392	104	.....	20	.....
15	Tr.	88	31	10		.0	332	51	17	12	399
.....	.5	.....	.....	.....	.....	.....	365	70	.....	(*a*)	.....
.....	Tr.	.....	.....	.....	.....	.....	438	154	.....	945	.....
.....	1	.....	.....	.....	.....	.....	396	222	.....	24	.....
.....	Tr.	.....	.....	.....	.....	.....	480	106	.....	101	.....
.....	1	.....	.....	.....	.....	.....	456	154	.....	60	.....
.....	Tr.	.....	.....	.....	.....	.....	510	300	.....	91	.....
.....	Tr.	.....	.....	.....	.....	.....	535	208	.....	66	.....
.....	1	.....	.....	.....	.....	.....	372	98	.....	30	.....
.....	2	.....	.....	.....	.....	.....	413	91	.....	(*a*)	.....
.....	4	.....	.....	.....	.....	.....	533	222	.....	50	.....
.....	0	.....	.....	.....	.....	.....	413	222	.....	185	.....
14	.1	70	25	12		.0	294	29	10	2.9	316
.....	Tr.	.....	.....	.....	.....	.....	259	108	.....	50	.....
.....	0	.....	.....	.....	.....	.....	288	44	.....	10	.....
.....	0	.....	.....	.....	.....	.....	301	Tr.	.....	20	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	64	548
19	2.8	70	28	15		.0	361	13	Tr.	2.8	322
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	37	479
.....	1.8	.....	.....	.....	.....	.....	337	Tr.	.....	10	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	43	487
.....	0	.....	.....	.....	.....	.....	272	Tr.	.....	10	.....
.....	.3	.....	.....	.....	.....	.....	437	83	.....	81	.....
.....	.1	.....	.....	.....	.....	.....	269	64	.....	30	.....
.....	0	.....	.....	.....	.....	.....	343	61	.....	10	.....
16	2.9	88	32	8		.0	403	25	.....	12	383
.....	0	.....	.....	.....	.....	.....	312	43	.....	10	.....
.....	0	.....	.....	.....	.....	.....	316	38	.....	10	.....
.....	0	.....	.....	.....	.....	.....	373	68	.....	24	.....
.....	Tr.	.....	.....	.....	.....	.....	607	208	.....	646	.....
20	1.0	62	28	32	2.4	.0	396	2.1	4.0	5.9	344
.....	3.8	.....	.....	.....	.....	.....	434	Tr.	.....	10	.....
.....	0	.....	.....	.....	.....	.....	486	Tr.	.....	130	.....
.....	0	.....	.....	.....	.....	.....	330	(*b*)	.....	171	.....
.....	3	.....	.....	.....	.....	.....	437	Tr.	.....	Tr.	.....
.....	Tr.	.....	.....	.....	.....	.....	432	276	.....	20	.....
.....	Tr.	.....	.....	.....	.....	.....	206	Tr.	.....	14	.....
21	.3	102	31	12		.0	355	87	12	5.0	463
.....	0	.....	.....	.....	.....	.....	294	64	.....	14	.....
26	1.2	64	28	85		.0	438	.7	7.0	94	510
.....	0	.....	.....	.....	.....	.....	353	108	.....	45	.....
.....	.3	.....	.....	.....	.....	.....	284	94	.....	50	.....
.....	0	.....	.....	.....	.....	.....	342	60	.....	10	.....

b More than 850 parts.

RELATION OF QUALITY TO WATER-BEARING STRATUM.

The principal water-bearing strata in most of the wells of whose waters analyses are given in Table 1 comprise, as noted by Fuller, the alluvium, the sands and gravels of the glacial deposits, the till, the "Niagara" and "Clinton" limestones, the limestones and shales of the Richmond and Maysville formations, the Point Pleasant formation, and the St. Peter sandstone. Other formations yield some water, but sufficient information regarding the quality of their waters is not at hand. After the analyses had been grouped in accordance with the formations noted by Fuller, the figures representing the amounts of the principal constituents were averaged. The averages, rounded off to avoid appearance of fictitious accuracy, are given in Table 2, the first part of which shows the chemical composition of the waters in parts per million and the second the percentage composition of the anhydrous residues.

TABLE 2.—*Chemical composition in relation to geologic strata.*

Mineral content in parts per million.

Principal water-bearing stratum.	Number of analyses averaged.	Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium and potassium (Na + K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Chlorine (Cl).	Total solids.
Alluvium	63	15	1	90	30	.....	0	380	100	60	500
Gravel	17	25	1	90	30	20	0	400	50	25	440
Till	40	20	.5	100	40	50	0	400	140	90	640
"Niagara"	20	20	.5	80	40	20	0	360	80	25	440
"Clinton"	7	15	.2	.....	.....	.....	0	430	100	50	.....
Richmond and Maysville	25	20	.2	190	70	140	0	380	300	160	1,100
Point Pleasant	12	.....	7	.....	.....	.....	0	530	190	360	.....
St. Peter	6	30	10	5,000	800	14,000	0	350	700	36,000	57,000

Percentage composition of anhydrous residue.

Alluvium	.....	3	0	18	6	[a] 4	37	.....	20	12	.....
Gravel	.....	6	0	20	7	5	45	.....	11	6	.....
Till	.....	3	0	16	6	8	31	.....	22	14	.....
"Niagara"	.....	4	0	18	9	5	40	.....	18	6	.....
"Clinton"	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Richmond and Maysville	.....	2	0	18	6	13	18	.....	28	15	.....
Point Pleasant	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
St. Peter	.....	0	0	9	2	25	0	.....	1	63	.....

[a] Estimated.

Definite general conclusions regarding the chemical composition of the waters from the several water-bearing strata must be made with extreme caution. Consideration of the conditions under which the samples were collected and tested makes this evident. It is by no means certain that water from a well is a fair average sample of the water from a single sharply differentiated water-bearing stratum; indeed it is certain that many wells in this region are supplied from two or more distinct beds. As the primary purpose of the well

driller is to obtain an abundant supply he usually does not attempt to shut out any water that he may encounter except possibly that near the surface, which is known to be polluted. Consequently any deep well that penetrates more than one water-bearing stratum is likely to yield a mixture and though one kind of water may predominate the other kinds modify its quality by diluting it or by increasing its mineral content. Even if all the supplies but one were excluded during construction subsequent deterioration of the casing might cause holes and cracks through which they could enter. It is possible also that wells drawing water from one stratum may not afford samples that are typical of that stratum over a wide area, as seepage from other strata may cause local changes in character. Especially might such modification occur in the waters of the alluvium, which could be locally and also intermittently affected by entrance of water from near-by formations whose supplies are under greater hydrostatic pressure. The water entering shallow wells is intermittently modified by the diluting effect of rain, and deep wells may be indirectly but appreciably affected by similar dilution. Last but not by any means least important is the recognized fact that the draft on a well affects the quality of the water; such influence has been noticed by different observers in widely separated districts. The water from most new wells contains more mineral matter than that from the same wells after they have been used for some time. Waters from strata on which there is heavy draft are commonly lower in mineral content than those in strata not under heavy draft, probably because of the decreased duration of contact of the waters with the minerals; increased draft on some wells, however, results in increased mineral content, a phenomenon doubtless due to percolation of strongly mineralized waters from contiguous formations. No figures for the bases appear in many of the analyses in Table 1, and this lack of data casts still more uncertainty on general conclusions. After consideration of all these circumstances it can readily be understood that statements regarding the quality of the waters can not be interpreted too literally, and it is not surprising to find in Table 1 great variations in the chemical composition of waters presumably from the same bed.

WATERS OF LOW MINERAL CONTENT.

The most noticeable feature in Table 2 is the great similarity in composition of the waters from the alluvium, gravel, till, "Niagara," and "Clinton." The averages indicate that they are all alkaline-saline waters with calcium and bicarbonates predominating but with appreciable amounts of magnesium, sulphates, and chlorides. The

similarity in composition is brought out still more forcibly in the second part of the table, in which the statement in percentage of anhydrous residue removes the differences due to dilution. The waters are practically alike in their proportionate contents of calcium, magnesium, and the alkalies. The combined carbonic acid exceeds all other negative radicles in amount; it is present almost invariably in the bicarbonate form with free carbon dioxide, and when any normal carbonates occur they are very small in amount. According to the averages the waters in the till are most strongly mineralized, and study of the separate analyses seems to confirm this conclusion, many of them showing high chlorides and sulphates. The waters of the gravels apparently are lowest in their relative amounts of chlorides and sulphates. The greatest differences between the waters occur in the proportion of chlorides.

Examination of the individual analyses in Table 1 affords additional proof not only that these waters are all of the same type but also that the wells yield from the same formation waters more radically different from each other than the averages of the analyses of waters from different formations; thus it can be seen that the sources of supply in the alluvium, gravel, till, and upper limestones can not be differentiated from the data at hand. The normal variations of bicarbonates, sulphates, chlorides, and total solids of waters from these strata are given in Table 3. Some evidently erroneous figures have been omitted from consideration and some of the amounts are estimates. The figures opposite the designation "approximate mean" have been rounded off to avoid fictitious accuracy.

TABLE 3.—*Differences in mineral content of wells in southwestern Ohio.*

[Parts per million.]

Source of water.	Bicarbonate radicle (HCO_3).		Sulphate radicle (SO_4).		Chlorine (Cl).		Total solids.	
	Highest.	Lowest.	Highest.	Lowest.	Highest.	Lowest.	Highest.	Lowest.
Alluvium	679	121	406	Tr.	380	Tr.	635	309
Gravel	630	320	154	Tr.	165	2	516	293
Till	607	206	362	Tr.	216	2	637	332
"Niagara"	470	265	362	Tr.	86	3	537	242
"Clinton"	535	305	222	Tr.	126	1	700	290
Approximate mean	600	240	300	Tr.	200	2	600	300

These figures give the highest and lowest amounts of certain substances according to the analyses in Table 1. The information regarding the amounts of calcium, magnesium, and sodium is insufficient to justify similar figures for them, but the amounts of the bases are roughly proportional to the amounts of the acids. The supplies

from these strata range from 300 to 600 parts per million of total solids and they may contain from 2 to 200 parts of chlorides, from a trace to 300 parts of sulphates, from 240 to 600 parts of bicarbonates, and calcium, magnesium, sodium, and potassium in proportion. There is no proof that any stratum may not yield waters reaching the highest or the lowest limits in mineral content, though the waters of the alluvium are likely to show the greatest and those of the "Niagara" and the "Clinton" the least differences. Probably this is due to the fact that the alluvium is exposed to greater modification by seepage from other formations and by percolation of surface water. It is evident from Table 3 that waters apparently from the same stratum differ very widely in mineral content, and consequently the averages in Table 2 can be interpreted as being indicative only of the general similarity of the waters.

The alluvium in some parts of the United States yields waters lower in mineral content than other local formations, and that might be thought to be a general condition, as the alluvial matter has been more thoroughly leached both during and after its deposition. The alluvial deposits in southwestern Ohio, however, are essentially calcareous, and they will furnish calcium and magnesium to the waters percolating through them just like other lime-bearing beds. In addition, most of the water entering this alluvium has previously become impregnated with mineral matter from other underground deposits which it has traversed. As a result the waters of the alluvium, though abundant, are not distinctly less mineralized than those of the other unconsolidated beds.

WATERS OF HIGH MINERAL CONTENT.

Though the waters of the unconsolidated deposits and of the upper limestones are similar, waters below the "Clinton" are sharply differentiated. Reference to Table 2 shows that the Richmond and Maysville formations yield supplies two to four times as high in mineral ingredients as those in the later formations and distinctly different in character. The percentages of calcium, magnesium, and chlorides are about the same, though the actual amounts are greater; the percentages of alkalies and sulphates are much greater, and the proportion of bicarbonates is much less. Tests of the water in the Point Pleasant are available only at Cincinnati, and these are incomplete, so that definite statements can not be made regarding the character of the supply; apparently it is similar to that of the Richmond and Maysville formations, possibly being higher in chlorides and in iron. No analyses of water from the Eden shale or from the "Birdseye" limestone are at hand, but the water in the former prob-

ably is as highly mineralized as that of the Richmond and Maysville, and the water in the "Birdseye" limestone is salty. The St. Peter sandstone yields in this region a very hard and very salt water, ranging from 1,000 to 100,000 parts per million of dissolved matter. Its characteristics as a strong brine can be seen in Table 2.

RELATION TO OTHER UNDERGROUND WATERS.

Table 4 presents figures by which the underground waters of southwestern Ohio may be compared with those of north-central Indiana, where limestones are abundant. Both regions are well supplied with rain and are areas of hard limestone, and it is therefore interesting but not surprising that their characteristic waters are similar in mineralization and in composition.

TABLE 4.—*Comparison of the quality of ground waters in southwestern Ohio and north-central Indiana.*

Mineral content in parts per million.

	Number of analyses averaged.	Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium and potassium (Na+K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Chlorine (Cl).	Dissolved solids.
A	120	20	0.8	90	35	30	0	390	90	50	500
B	169	18	.8	91	31	18	0	306	76	47	467
C	20	20	.5	80	40	20	0	360	80	25	440
D	80	18	1.8	82	31	27	0	341	70	19	466

Percentage composition of the anhydrous residues.

E		4	0	18	7	5	38		18	10	
F		4	0	21	7	4	35		18	11	
G		4	0	18	9	5	40		18	6	
H		4	0	20	7	7	40		17	5	

A, E, Unconsolidated deposits of southwestern Ohio.
B, F, Unconsolidated deposits of north-central Indiana (Water-Supply Paper U. S. Geol. Survey No. 254, 1910, pp. 260 and 261).
C, G, "Niagara" limestone of southwestern Ohio.
D, H, Fresh-water limestones of north-central Indiana.

SURFACE WATERS.

Samples of water collected daily from Miami River at Dayton by B. F. Glass were united in sets of 10 and analyzed, with the results stated in Table 5. Daily readings of the gage maintained at Dayton by the Weather Bureau were averaged in groups corresponding to the sampling periods, and these averages are given in the last column of the table. By comparing the gage heights with the amounts of suspended and dissolved solids an idea may be gained of the relation between the quantity of the water and its quality at this place.

TABLE 5.—*Mineral analyses of water from Miami River at Dayton.*[a]

[Parts per million unless otherwise designated.]

Date (1906–7).		Turbidity.	Suspended matter.	Coefficient of fineness.	Total iron (Fe).	Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium and potassium (Na + K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chloride (Cl).	Total dissolved solids.	Mean gage height (feet).
From—	To—																
Sept. 16	Sept. 25	32	75	2.34	3.1	16	Tr.	58	28	10	9.0	264	38	0.9	5.0	300	0.7
Sept. 26	Oct. 5	32	58	1.81	.9	21	Tr.	65	28	9.0	9.0	280	35	2.8	5.8	318	.8
Oct. 6	Oct. 15	18	32	1.78	.4	17	Tr.	63	26	9.6	.0	297	37	3.1	5.0	309	.6
Oct. 16	Oct. 25	14	26	1.86	.10	18	Tr.	65	27	9.0	.0	301	40	2.9	5.0	317	.8
Oct. 26	Nov. 4	5	14	2.80	.15	20	Tr.	66	28	11	8.2	291	41	2.0	5.5	327	1.0
Nov. 5	Nov. 14	8	20	2.50	Tr.	20	Tr.	69	29	9.8	Tr.	317	41	2.0	5.3	335	2.0
Nov. 15	Nov. 24	75	89	1.19	2.1	14	0.24	64	27	9.8	11	250	40	7.0	4.3	304	2.8
Nov. 25	Dec. 4	16	21	1.31	.5	19	.05	75	28	7.4	3.6	278	60	15	4.0	346	2.4
Dec. 5	Dec. 14	26	34	1.31	.7	26	.07	75	28	8.2	10	269	62	12	4.7	355	2.5
Dec. 15	Dec. 24	80	54	.67	1.4	15	.23	64	23	6.8	.0	239	52	13	3.0	296	3.0
Dec. 25	Jan. 4	.....	177	.....	3.2	16	.19	68	24	7.1	.0	272	52	12	3.5	318	4.2
Jan. 5	Jan. 14	210	118	.56	3.0	14	.5	50	17	6.5	.0	184	36	18	3.6	238	6.5
Jan. 15	Jan. 24	450	223	.50	6.7	15	.7	42	14	7.1	.0	161	29	11	3.4	212	7.5
Jan. 25	Feb. 4	75	49	.65	1.8	16	.6	61	23	8.8	12	229	44	16	4.1	301	3.3
Feb. 5	Feb. 14	45	42	.93	.5	8.8	.05	60	26	8.0	12	215	51	10	3.8	282	2.9
Feb. 15	Feb. 24	11	28	2.55	.4	24	.06	58	25	6.9	13	212	42	11	4.1	298	2.8
Feb. 25	Mar. 6	260	143	.55	4.2	25	.08	67	25	7.4	8.4	246	49	9.0	3.8	320	2.9
Mar. 27	Apr. 6	37	52	1.41	1.0	15	.12	64	24	8.0	12	228	44	10.0	4.6	299	2.2
Apr. 7	Apr. 16	25	67	2.68	.3	20	.14	50	26	8.4	12	200	44	15	5.4	282	2.1
Apr. 17	Apr. 26	25	32	1.28	.6	19	.11	58	25	3.5	16	217	41	15	4.2	298	2.2
Apr. 27	May 6	20	36	1.80	.4	15	.16	62	24	6.3	13	229	39	19	3.8	297	2.5
May 7	May 16	18	35	1.94	.4	23	.11	58	23	3.3	14	217	40	18	4.3	292	2.0
May 17	May 28	37	79	2.14	1.3	14	.10	52	26	3.0	12	218	41	15	3.8	275	1.8
May 29	June 8	240	186	.77	4.4	19	.19	53	20	12	10	197	34	15	4.8	264	2.8
June 9	June 18	280	252	.90	7.0	18	.7	49	18	11	9.6	180	27	17	3.8	252	5.2
June 19	June 28	75	75	1.00	2.6	17	.12	60	22	11	2.4	249	33	6.2	4.8	283	2.5
June 29	July 8	90	168	1.86	1.6	17	.03	42	26	8.2	.0	206	37	1.2	4.2	240	1.9
July 9	July 19	.....	351	.....	7.9	30	.35	51	20	14	.0	.....	20	6.4	2.4	254	4.0
July 20	July 29	.....	234	.....	3.2	8.6	.04	26	18	12	.0	.....	32	Tr.	.6	163	3.4
July 30	Aug. 8	.....	125	.....	1.6	9.2	Tr.	56	24	12	.0	.....	37	1.5	.6	258	2.2
Aug. 9	Aug. 18	.....	77	.....	1.0	18	.03	55	25	11	.0	.....	39	1.5	1.4	273	1.4
Aug. 19	Aug. 28	35	48	1.37	.9	9.8	.05	69	29	12	.0	323	34	.0	5.4	331	1.1
Aug. 29	Sept. 7	43	46	1.07	.9	15	.04	63	24	14	.0	287	41	2.5	5.8	304	1.2
Sept. 8	Sept. 17	140	130	.93	2.6	19	.13	59	25	13	.0	251	36	2.2	4.8	289	1.7
Mean		84	94	1.46	2.0	17	.15	59	24	9.0	5.8	244	40	8.6	4.1	289	....
Per cent of anhydrous residue		.....	.....	.....	.....	5.9	[b].1	20.5	8.3	3.1	43.8	.....	13.9	3.0	1.4	..	....

[a] Analyses Sept. 9 to Dec. 4, 1906, by R. B. Dole; Dec. 5, 1906, to Mar. 6, 1907, by R. B. Dole and M. G. Roberts; Mar. 27 to June 28, 1907, by Chase Palmer and M. G. Roberts; June 29 to Sept. 17, 1907, by R. B. Dole, Chase Palmer, and W. D. Collins. Water-Supply Paper U. S. Geol. Survey No. 236, 1909, p. 72.

[b] Fe_2O_3.

During 1898 daily samples of water were taken from one of the intakes in Ohio River at Cincinnati, and the average, maximum, and minimum conditions of the water of Ohio River as shown by these analyses are given in Table 6.[1]

TABLE 6.—*Mineral analyses of water from Ohio River at Cincinnati, 1898.*

[Parts per million.]

	Maximum.	Minimum.	Average.
Suspended solids	2,333	24	230
Dissolved solids	233	67	120
Carbonate radicle (CO_3)	.0	.0	.0
Bicarbonate radicle (HCO_3)	85	24	55
Sulphate radicle (SO_4)	46	13	24
Nitrate radicle (NO_3)	1.34	.37	.60
Chlorine (Cl)	44	3.0	10

[1] Fuller, G. W., Report on the investigations into the purification of the Ohio River water for improved water supply of the city of Cincinnati, Ohio, 1899, pp. 493–494.

The miscellaneous analyses of surface waters in southwestern Ohio presented in Table 7 are not absolutely comparable because of differences in the analytical procedures employed by the analysts. The greatest difference probably is in total solids. It has been customary in the laboratory of the Geological Survey to dry residues at 180° C. for one hour. Horton dried his residues at slightly less than 100° C. and Dudley at 110° C. Therefore varying amounts of water, organic matter, and other volatile material are included in the figures for total solids. Most of the large differences, however, are probably due to actual differences in the waters at the time of collecting the samples.

TABLE 7.—*Miscellaneous analyses of surface waters in southwestern Ohio.*

[Parts per million unless otherwise designated.]

Source.	Analyst.	Date.	Silica (SiO_2).	Oxides of iron and aluminum ($Fe_2O_3+Al_2O_3$).	Calcium (Ca).	Magnesium (Mg).	Sodium and potassium (Na+K).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Chlorine (Cl).	Total solids.	Probable incrustants.
East Fork of Little Miami River:												
Lynchburg	E. G. Horton	April, 1905	....	....	55	25	....	....	48	4.0	223	....
Batavia	do	(a)	....	....	....	....	....	165	....	14	258	....
Little Miami River:												
South Charleston	do	(a)	....	....	....	....	....	298	....	.9	244	....
Goes	C. B. Dudley	Sept. 12, 1901	....	....	....	....	....	....	....	6	315	262
Do	Kennicott Water Softener Co.	Apr. 21, 1903	5.5	2.0	87	16	8.0	286	44	12	316	....
Trebeins	J. W. Ellms	Mar. 21, 1902	....	....	74	22	....	272	45	....	....	282
Do	do	Aug. 8, 1904	....	....	56	29	5.6	300	24	3.6	....	252
Xenia	E. G. Horton	(a)	....	....	....	....	....	304	....	.9	371	....
Do	Kennicott Water Softener Co.	Aug. 12, 1902	2.4	2.9	75	37	....	286	60	24	....	....
Morrow	C. B. Dudley	Oct. 24, 1893	....	....	....	....	....	....	....	7	260	220
Loveland	do	Sept. 28, 1896	....	....	....	....	....	....	....	7	304	253
Do	do	June 30, 1898	....	....	....	....	....	....	....	14	307	244
Do	E. G. Horton	(a)	....	....	....	....	....	244	....	1.9	364	....
Linwood	do	(a)	....	....	....	....	....	205	....	2.3	679	....
Mad River:												
Urbana	do	(a)	....	....	....	....	....	340	....	1.2	456	....
Springfield	do	(a)	....	....	....	....	....	332	....	.5	431	....
Dayton	do	(a)	....	....	....	....	....	311	....	2.8	417	....
East Dayton	J. W. Ellms	July 23, 1904	....	....	71	32	9	314	51	8	....	303
Do	do	Jan. 23, 1904	....	....	61	20	....	224	37	8	....	238
Mill Creek:												
Reading	C. B. Dudley	Sept. 29, 1893	....	....	....	....	....	....	....	Tr.	329	271
Ivorydale	J. W. Ellms	Dec. 9, 1904	....	....	75	28	18	312	58	14	....	299
Do	do	July 23, 1904	....	....	45	23	11	220	35	10	....	202
Do	do	Nov. 16, 1903	....	....	89	26	26	328	56	41	....	335
Do	do	Sept. 16, 1902	....	....	101	31	21	442	16	31	....	368
Do	do	Feb. 21, 1902	....	....	94	34	....	364	69	13	....	....
Miami River:												
Sydney	do	Feb. 18, 1901	....	....	86	35	4	284	115	7	....	377
Do	do	May 22, 1902	....	....	81	33	3	294	77	10	....	346
Do	E. G. Horton	(a)	....	....	....	....	....	268	....	.7	404	....
Piqua	do	(a)	....	....	....	....	....	245	....	1.2	484	....
Troy	do	(a)	....	....	....	....	....	262	....	2.4	388	....
Do	J. W. Ellms	Feb. 11, 1902	....	....	75	32	34	372	67	6	....	298
Do	do	Nov. 10, 1903	....	....	64	23	16	262	54	12	....	251
Do	do	July 27, 1904	....	....	53	23	4	222	45	3	....	229
Do	do	Dec. 9, 1904	....	....	64	23	5	262	41	5	....	256

a Average of 8 analyses of water collected between April and November, 1900.

TABLE 7.—*Miscellaneous analyses of surface waters in southwestern Ohio*—Continued.

Source.	Analyst.	Date.	Silica (SiO_2).	Oxides of iron and aluminum ($Fe_2O_3+Al_2O_3$).	Calcium (Ca).	Magnesium (Mg).	Sodium and potassium (Na+K).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Chlorine (Cl).	Total solids.	Probable incrustants.
Miami River:												
Dayton	E. G. Horton	(*a*)	....	....	....	....	....	278	....	4 2	407	....
Do	J. W. Ellms	(*b*)	....	....	79	30	4	292	64	11	....	323
Middletown	E. G. Horton	(*a*)	....	....	....	....	....	259	....	3 3	423	....
Hamilton	do	(*a*)	....	....	....	....	....	230	....	3 1	626	....
Twin Creek:												
Carlisle	J. W. Ellms	(*c*)	....	....	62	25	3	272	27	2	....	247
Whitewater River:												
New Paris	C. B. Dudley	Feb. 23, 1893	....	....	....	....	....	....	....	....	334	248
Pond:												
College Corner	J. W. Ellms	(*d*)	....	....	60	33	16	236	79	30	....	294

a Average of 8 analyses of water collected between April and November, 1900.
b Average of 20 analyses of water collected at intake, North Dayton, at Second Street, Dayton and at Perry Street, between Feb. 28, 1901, and Mar. 7, 1906.
c Average of 4 analyses of water collected between Feb. 21, 1902, and Dec. 9, 1904.
d Average of 5 analyses of water collected from a pond between Dec. 8, 1900, and Dec. 9, 1904.

Comparison of Table 6 with Tables 5 and 7 indicates that the water of Ohio River at Cincinnati is lower in mineral content than the other surface waters of this region. This is due to the fact that the greater portion of the Ohio comes from areas of soft water. The Allegheny at Kittanning, Pa., carries 87 parts per million of dissolved solids and the Monongahela at Elizabeth, Pa., 81 parts; and though Youghiogheny River at McKeesport, Pa., carries 197 parts of dissolved solids it contributes only about one-eighth of the discharge of Ohio River at Pittsburgh, Pa., and therefore its water does not much increase the mineral content of the main stream. The tributaries from the State of Ohio are similar to Miami River in mineral content, but their effect is more than counterbalanced by the drainage from Kentucky and West Virginia, which is much lower in dissolved solids.

RELATION BETWEEN UNDERGROUND AND SURFACE WATERS.

The surface supplies are much lower in mineral content than the ground supplies, and are therefore better for industrial use. The relation between the quality of the water of Miami River at Dayton and those of the underground sources is shown in Table 8. The ground waters in general exceed the Miami water in their content of all constituents, but the character of the mineral matter is much the same in both.

TABLE 8.—*Comparison of the mineral content of surface and underground waters.*

Mineral content in parts per million.

	Silica (SiO_2).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium and potassium (Na+K).	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Nitrate radicle (NO_3).	Chlorine (Cl).	Dissolved solids.
A	17	0.15	59	24	9.0	5.8	244	40	8.6	4.1	289
B	20	.8	90	35	30	0	390	90	.....	50	500

Percentage composition of anhydrous residues.

C	5.9	a 1	20.5	8.3	3.1	43.8	.....	13.9	3.0	1.4	.....
D	4	0	18	7	5	38	.....	18	.....	10	.....

a Fe_2O_3.

A, C, Water of Miami River at Dayton.
B, D, Underground water; from gravel, till, "Niagara," and "Clinton."

ECONOMIC VALUE OF THE WATERS.

The best source of large amounts of water for industrial purposes in this region is Ohio River, whose waters are much lower in dissolved solids than its tributaries from southwestern Ohio and only from one-fifth to one-third as high in dissolved solids as the ground waters of low mineral content. Practically all the surface waters are lower in mineral content than the ground waters and consequently are better for industrial use. In addition to dissolved matter, the water of Ohio River averages 230 parts and that of Miami River 94 parts per million of suspended solids, but it would be much less expensive to remove the suspended matter from these waters than to soften available ground waters that do not contain suspended matter. If the turbidity were removed by sedimentation or by filtration the surface waters could be classified as good to fair for boiler use and most of them could be used without further treatment.

The waters from the alluvium, gravel, till, "Niagara" limestone, and "Clinton" limestone are similar in mineral content and in the character of their dissolved matter. Dissolved solids range from 300 to 600 parts per million and average about 500 parts, chlorides from 2 to 200 parts, sulphates from a trace to 300 parts, and bicarbonates from 240 to 600 parts. The waters are hard, but they can readily be softened, and in their natural condition they range from fair to bad for boiler use; they deposit considerable scale and some of them are corrosive, but they do not foam under ordinary conditions of boiler operation.

The waters from the Richmond and Maysville formations and from the Point Pleasant are distinctly less desirable as industrial supplies, being much higher in incrustants, chlorides, and sulphates.

Though some of the waters from the Richmond and Maysville are as low in incrustants as some of the waters from the later beds, the results of the few analyses available indicate that this is not their general condition.

The St. Peter sandstone yields water so heavily mineralized as to be unfit for industrial use except for cooling, and even for that purpose the water would be corrosive.

As practically all the surface waters in this region are likely to be polluted by sewage and most of them by factory wastes they should not be used for domestic supplies without careful purification. Filtration under competent supervision would probably make them safe for drinking and satisfactory for laundry use. Nothing in the averages of the analyses of fresh underground waters indicates that they are not suitable for drinking and for general domestic use, though those from the earlier formations are very hard. Consideration of the individual analyses, however, shows that some of the waters contain so much iron that they would stain fabrics washed in them. The pollution of streams in this region and the sources of waters in relation to municipal use have been studied in much detail by the State board of health.[1]

[1] Ann. Repts. Ohio State Board of Health, 1897 to date.

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PRELIMINARY REPORT

ON THE

GROUND WATERS OF ESTANCIA VALLEY NEW MEXICO

BY

OSCAR E. MEINZER

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PRELIMINARY REPORT ON THE GROUND WATERS OF ESTANCIA VALLEY, NEW MEXICO.

By Oscar E. Meinzer.

INTRODUCTION.

LOCATION AND AREA.

Estancia Valley lies near the geographic center of New Mexico, south of Santa Fe and east of Albuquerque. The valley is a depression with no drainage outlet. It has a maximum extent of about 65 miles north and south and 40 miles east and west, and includes an area of about 2,000 square miles.

GEOGRAPHIC RELATIONS.

On the west Estancia Valley is separated from the Rio Grande valley by a mountain wall; on the east it is bordered by a maze of hills which divide it from the upland that slopes toward the Pecos Valley; on the north it rises gradually until it ends abruptly as a plateau overlooking the valley of Galisteo Creek, which flows westward into the Rio Grande; on the southwest it is terminated by a mesa; and on the southeast, where it is hemmed in between the mesa and the hills, it is separated by a low divide from another closed basin.

DEVELOPMENT.

This valley has long supported a sparse population. Nestled in the western foothills, remote from any city or railroad, the Mexican villages of Chilili, Tajique, Torreon, Manzano, and Punta de Agua have for generations led a peaceful but primitive existence, their inhabitants depending for a livelihood chiefly on their flocks of sheep. Moreover, planted here and there on the broad, level expanses of the valley proper are isolated establishments which have been the homes of independent and prosperous ranchers, most of whom are Mexicans.

But within the last decade a great change has taken place in this region. Two railways have been built—the Santa Fe Central, which traverses the entire length of the valley, and the "Belen cut-off" of

the Atchison, Topeka and Santa Fe Railway, which crosses its southern part. Hundreds of homesteaders have come to take possession of the land, and eight villages have sprung up along the railways.

INVESTIGATION AND REPORTS.

Insufficient rainfall during recent years has caused crop failures and has created an urgent demand for an investigation of the feasibility of irrigating with ground water. In response to this demand and for the purpose of classifying the land under the enlarged-homestead act, an examination of the valley covering a period of six weeks was made by the writer in the summer of 1909. The time available was not sufficient to permit a thorough investigation. Hence attention was given especially to the more pressing and practical phases of the problem.

A report embodying all the results of the work has been prepared, but this report contains maps and other illustrations which will delay its publication, so that some months must elapse before it will be ready for distribution. In view of the rapid development now under way in the valley and the immediate need of the settlers there for all the definite information that can be supplied, it has seemed desirable to abstract from the complete report the facts and deductions that are of most practical value and to publish them in this brief preliminary paper.

OUTLINE OF THE GEOLOGY.

VALLEY FILL.

The hard rock floor of Estancia Valley is covered by deposits that may be grouped under the general term "valley fill." Nearly all these sediments came originally from the highlands that border the valley and are the product of thousands of years of weathering and denudation. The erosive processes which have carved the canyons and given form to the serrate peaks have at the same time supplied the material that has accumulated in the lowlands as the valley fill.

WORK OF THE STREAMS.

DISTRIBUTION OF THE ALLUVIAL DEPOSITS.

Apparently the bulk of the valley fill consists of alluvial deposits—that is, of materials laid down by streams and not rehandled by any other agency. Such deposits underlie the broad belt comprising the alluvial slopes, are interbedded and intermingled with lake deposits in the littoral zone, as can be seen in many natural and artificial exposures, and probably occur at no great depths below the lake sediments in the lake flat and clay hill area. Their relation to the lake deposits can be best understood after the latter have been described (p. 8).

The alluvial material is much thicker in some localities than in others. If the interpretations of the well sections are correct, the total thickness of the valley fill is 312 feet at Willard, 225 feet in the test wells 4 miles east of Estancia, and 233 feet in H. C. Williams's well south of Estancia. L. Knight's deep well (in the NE. ¼ sec. 1, T. 5 N., R. 8 E.) was carried to a depth of 240 feet without encountering rock. In many parts of the valley, however, especially on its east and west margins, the alluvium is much thinner and rock crops out.

ORIGIN OF THE ALLUVIAL DEPOSITS.

The alluvial deposits were laid down by streams which were probably intermittent and exceedingly irregular in their flow, depending then, as now, chiefly on the sudden and capricious visitations of heavy local storms. The work of these streams was correspondingly capricious and variable; at one place they eroded, only to deposit a little farther on the load which they thus picked up; at one place they left behind coarse gravel, and at another they laid down only fine silt. The same locality was at different times subjected to all these conditions and, moreover, by the frequent changing of the courses of the streams, was at one time an arroyo and at another an interstream area. It is therefore not surprising that the alluvial deposits consist of heterogeneous beds which have little continuity or regularity, and that two wells in the same locality should have quite different sections.

CHARACTER OF THE ALLUVIAL DEPOSITS.

Most of the alluvial material consists of clay with which are associated pebbles and bowlders of different sizes and composition. In general the pebbles and bowlders decrease, both in size and abundance, from the mountain borders, where bowlder beds with little or no clay may occur, toward the central portion of the valley, where clay virtually free from pebbles may be found. But though coarse materials form a larger proportion of the mass in the regions near the mountains than in the interior, yet well sections furnish abundant proof that beds of clean gravel and sand occur in the very heart of the valley. The composition of the pebbles depends on the kind of rocks that constitute the uplands and the resistance of these rocks to weathering and wear. On the whole, pebbles of limestone are by far the most numerous, because this rock is well represented in the uplands, especially on the west, and is also resistant in character.

WORK OF THE LAKE.

At its period of greatest extension the lake that occupied the central portion of the valley was about 35 miles long and 23 miles wide and had an area of about 450 square miles. Its maximum depth at this

period was almost 150 feet, and its shore line, which nearly coincides with the 6,200-foot contour, was about 150 miles long. If this lake were now in existence the villages of Estancia and Willard would be 100 feet under water; McIntosh and Progreso would also be submerged; Moriarty and Lucy would virtually be lake ports; and Stanley, Mountainair, and Cedar Vale would be inland towns. The higher ground which surrounded the lake has been explored everywhere, but no outlet channel has been found and it is therefore certain that the lake had no outlet and that its water was salt.

The theory of the existence of an ancient lake in the valley is based on the presence of shore features and lake sediments.

SHORE FEATURES.

Within the littoral zone there are sea cliffs, terraces, beaches, beach ridges, spits, and bars. These features are found on all sides of the lake flat between the altitudes of 6,100 and 6,200 feet above sea level.

LAKE SEDIMENTS.

Beach material.—Most of the material constituting the beaches, beach ridges, spits, and bars is gravel. The pebbles are waterworn and many of them are covered with a gray coat of lime. The best exposures of beach material are found in the gaps that have been cut through the bars.

Stratified sediments.—Except where the salt basins and clay hills occur, the large area inclosed by the shore zone is exceedingly flat; but the salt basins are excavated to depths of 10 to 20 feet and more in the material under this plain, and their sides are generally steep and thus expose the strata to good advantage. Wells have also been dug and these are usually left uncased, showing the materials through which they extend. Moreover, many cellars and dugouts have been made, most of which likewise remain unlined. Ample opportunity is therefore afforded to examine the formation which immediately underlies the plain. This formation is totally different from that which underlies the alluvial slopes. It is perfectly stratified, consisting of innumerable thin layers lying one upon another, each layer traceable for an indefinite distance. It is precisely the kind of deposit which would be formed at the quiet bottom of a large body of standing water and which could be formed in no other manner. It was observed in many exposures, natural and artificial, and in widely separated localities. It is practically coextensive with the lake flat and clay hills area and can be seen wherever there is a salt basin, a dug well, a cellar, or any other excavation.

Clay or shale constitutes the bulk of the material, but layers of sand are also present and beds of grit and fine gravel were observed near the outer margin of the lake flat.

Of the thickness of the lake sediments little is definitely known, but the available evidence indicates that they are relatively thin and are underlain at no great depth by alluvial deposits. The principal evidence concerning their thickness is found in the beds of alluvial gravel encountered in drilling on the lake flat and in the transition in many wells from grayish lake sediments near the surface to alluvial deposits of red clay at greater depths.

WORK OF THE WIND.

On the east side of the valley there are great masses of wind-blown sand, the largest accumulations being found east of McIntosh, in the west-central part of T. 6 N., R. 11 E., and in an adjacent area to the west, and in certain localities both north and south of Progreso. Much of this sand is heaped into fresh dunes and is at present being handled by the winds.

SALT BASINS AND CLAY HILLS.

The salt basins are found in the lowest portion of Estancia Valley. They are not, however, remnants of the ancient lake—not merely low spots in which the surplus water collects until it is dissipated by evaporation—but are distinct basins sunk below the level of the plain by which they are surrounded, and most of them are bordered by definite, nearly vertical walls. Their flat bottoms practically coincide with the ground-water level and generally consist of mud covered with crusts of salt, although after rains they may be submerged in water. The floor of one basin—Laguna Salina, in secs. 29 and 30, T. 5 N., R. 10 E.—is covered with salt sufficiently thick and pure to be commercially valuable.

Altogether there are several score of salt basins with a total area estimated at 13,500 acres. In this assemblage Laguna del Perro assumes relatively gigantic proportions, having a length of about 12 miles and an area nearly equal to the combined area of all the other basins.

Intimately associated with the salt basins are the clay hills. Within the area in which they exist there are many level tracts which are essentially a part of the original plain. The highest clay hills rise more than 100 feet above the plain on which they rest, but most of them are perhaps less than 50 feet high.

Typically they form huge embankments which more or less completely encircle the salt basins. This form is so common that the traveler on approaching a hill or ridge confidently expects to find a salt basin on the other side.

SOILS.

RED LOAMY SOIL.

The most widely distributed soil in the valley consists of red clay intermingled with varying quantities of grit and gravel. It is seen in typical character in the alluvial slopes and arroyos, but it also occurs throughout much of the littoral zone and is found far up in the foothills. It is essentially the product of the weathering of the rocks in the surrounding highlands, whence it has been washed out into its present position in the manner already described. In general this soil is very fertile, as is demonstrated by the large crops that it produces when climatic conditions are not unfavorable, and its fertility is due largely to its content of soluble substances which serve as plant food. These soluble substances have been produced by the weathering of the rocks and have not been leached out from the soil by percolating waters to so great an extent as in more humid regions.

SANDY SOILS.

Sandy soils are found chiefly on the east side of the valley. They range from clean, pale-yellow dune sand, which is worthless for agriculture, to red, earthy sand and red sandy loam, which may be very productive. Sandy soils, like clay and loam soils, have been deprived of less of their soluble constituents in arid than in humid regions.

ALKALI SOILS.

It has just been stated that most of the soil in Estancia Valley, as in arid and semiarid regions generally, is very fertile because of the soluble substance which it contains. But if certain soluble substances, commonly known as alkalies, exist in soils in quantities too large, they are injurious to plant life; hence very fertile soils grade readily into alkali soils; and, moreover, soils which at first are very productive may, after a period of irrigation and cultivation, become harmfully alkaline. On this point Milton Whitney,[a] chief of the Bureau of Soils, United States Department of Agriculture, makes the following statement:

> This accumulation explains the wonderful fertility of the lands generally in the arid regions the world over, but it is also a constant menace because of the large amount of soluble salts which is liable to accumulate locally as the result of irrigation or as a result of other natural conditions not well understood, until they are a menace and often a destructive agency for the very lands which were formerly held in such esteem.

The different kinds of alkali and their effects upon vegetation can best be explained by a further quotation from Whitney, as follows:

> The alkali soils of the West are of two principal classes. The alkaline carbonates or black alkali (usually sodium carbonate) is the worst form, actually dissolving the organic materials of the soil and corroding and killing the germinating seed or roots of

a Alkali lands: Farmers' Bull. No. 88, U. S. Dept. Agr., 1899, p. 7.

plants; the white alkalies, the most common of which are sodium sulphate (Glauber's salt), sodium chloride (common salt), magnesium sulphate, and magnesium chloride, are not in themselves poisonous to plants, nor do they attack the substance of the plant roots, but are injurious when, owing to their presence in excessive amounts, they prevent the plants from taking up their needed food and water supply.

The amount of soluble salts which plants can stand depends upon the character of the salt, the character of the soil, and the kind of plant. Hilgard states that few plants can stand as much as 0.1 per cent of sodium carbonate; of sodium chloride plants can stand about 0.25 per cent, and of sodium sulphate 0.45 to 0.5 per cent. Plants can stand less salts in sandy lands than on heavy clay or gumbo lands. It is a well known fact that crops also differ in their ability to stand salts, and many crops will grow well upon soils on which others will not live.

Investigations at Billings, Mont., showed that when the concentration of the salts in active solution in the soil moisture is as great as 1 per cent the limit of most cultivated plants is reached. Further concentration kills all our ordinary agricultural crops. It was found, furthermore, that plants could just exist with 0.45 per cent of the soluble salts present, and this is taken as the limit of plant production.

A later statement by C. W. Dorsey,[a] of the Bureau of Soils, is as follows:

Of the different classes of alkali, sodium carbonate, or black alkali, is considered the most injurious. Laboratory experiments have shown that magnesium chloride and sulphate are as injurious, if not more injurious than sodium carbonate. After these salts comes sodium chloride (ordinary salt) and sodium sulphate. When present in soils to the exclusion of other salts, 0.05 per cent of sodium carbonate presents about the upper limit of concentration for common crops. One-half of 1 per cent of sodium chloride is commonly regarded as the endurance limit of crops, and 1 per cent of sodium sulphate. Sodium sulphate, then, is the least injurious and sodium carbonate the most injurious of the salts usually constituting the greater part of alkali under ordinary field conditions, while sodium chloride occupies a middle position.

Gypsum (calcium sulphate) acts as an antidote for black alkali by reacting with it to form (1) calcium carbonate, which is harmless, and (2) sodium sulphate, which is a less injurious white alkali. A soil that contains a large amount of gypsum would therefore not be expected to contain much black alkali, although it may contain some.[b]

In Estancia Valley the shallow-water belt, the ancient lake bed, the area of highly mineralized waters, and the area in which the most alkaline soils are found all coincide approximately with one another, because all are results of the same general causal conditions. The rain that falls on the highland borders naturally flows toward the lowest area, where it accumulates until it is disposed of by evaporation. Whether it here stands slightly below the general surface of the ground, as at present, or a short distance above the surface, as during the Pleistocene epoch, when a lake existed, is merely an incident in the general circulation. The important facts in this con-

[a] Reclamation of alkali soils: Bull. Bureau of Soils No. 34, U. S. Dept. Agr., 1906, p. 10.

[b] Cameron, F. K., Application of the theory of solution to the study of soils: Field operations, Div. of Soils, 1899, U. S. Dept. Agr., 1900, pp. 152 et seq. Hilgard, E. W., Soils, Macmillan Co., New York, 1906, pp. 449 et seq., 457, 458.

nection are that in its course it dissolves and carries along the soluble constituents which it encounters in the rocks and soil, and that on its evaporation these soluble constituents are left behind, thus becoming concentrated in the lowest portion of the valley. The crusts of alkali which cover the salt basins are visible illustrations of the process that has impregnated with alkali the soil of the low area.

Samples of soil were collected at five points within the lake flat along a line extending eastward from Estancia for a distance of 6 miles, and these samples were analyzed by the United States Bureau of Soils with the following results:

Analyses of soil in Estancia Valley.

Location.	Depth within which the material was obtained.	Soluble solids (alkalies), per cent of total material.	Predominating salts in the order named.
	Feet.		
Estancia, NW. ¼ sec. 12, T. 6 N., R. 8 E., at the intersection of the railway with the section line.	1	0.2	Chlorides and bicarbonates.
	2	.3	Do.
	3	.8	Sulphates and chlorides.
	4	1.0	Do.
	5	1.2	Do.
	6	1.0	Do.
T. J. Moore, northeast corner of SW. ¼ sec. 5, T. 6 N., R. 9 E.	1	.1	Do.
	2	1.4	Chlorides and sulphates.
	3	1.3	Sulphates and bicarbonates.
	4	1.5	Do.
	5	2.1	Sulphates and chlorides.
	6	1.6	Do.
Southwest corner of sec. 4, T. 6 N., R. 9 E.....	1	.6	Do.
	2	.7	Chlorides and sulphates.
	3	3.7	Sulphates and chlorides.
	4	3.9	Do.
	5	3.7	Do.
	6	3.5	Do.
N. Williams, southwest corner of SE. ¼ sec. 3, T. 6 N., R. 9 E.	1	2.5	Do.
	2	2.7	Do.
	3	2.9	Do.
	4	2.7	Do.
	5	2.9	Do.
	6	3.5	Do.
H. N. Summers, southeast corner of SW. ¼ sec. 1, T. 6 N., R. 9 E.	1	1.6	Do.
	2	2.8	Do.
	3	3.7	Do.
	4	4.5	Do.
	5	3.6	Do.
	6	4.5	Do.

In respect to these analyses J. A. Bonsteel, in charge of soil surveys, writes:

It is apparent to the student of soils and soil conditions in the basin region that these soils are very heavily loaded with alkali salts, comparing more directly with those of old desiccated lake basins than with any of the agricultural lands now occupied in the United States. You will also notice the continual appearance of chlorides in practically all of the samples. From this I judge that the soil samples were taken from a decidedly alkaline tract, probably a desiccated lake bed. Only the most efficient tile underdrainage would render the majority of these soils capable of producing crops.

WATER.

SOURCE AND DISPOSAL.

If the mean annual precipitation for the entire Estancia basin is assumed to be 15 inches, the total amount of water that falls as rain or snow in an average year on the basin is approximately 1,600,000 acre-feet. If it is further assumed that within recent years the quantity of ground water has not materially increased nor decreased, it follows that the same amount is, on the average, withdrawn each year from the Estancia basin. This withdrawal is accomplished by evaporation into the atmosphere and by seepage through underground passages to lower points outside of the basin. No water leaves the basin in surface streams.

EVAPORATION FROM THE SURFACE.

Much of the water that falls as rain or snow returns to the atmosphere by being evaporated, either directly from the surface before it soaks into the ground or else after it has soaked a short distance into the ground, from which it is again withdrawn by vegetation or by capillary action in the soil. The proportion of moisture thus disposed of is greatest for the lightest showers and least for the heaviest and most persistent rains.

MOUNTAIN SPRINGS AND STREAMS.

Some of the moisture that falls on the mountains seeps into the pores and crevices of the rocks, but reappears at lower levels, where it issues in numerous springs that give rise to brooks or rivulets, most of which disappear long before they reach the valley, the water being dissipated both by evaporation and by seepage into the ground. Springs and streams of this type in the canyons and foothills of the Manzano Range have determined the location of the old Mexican settlements of Chilili, Tajique, Manzano, Punta de Agua, Torreon, and the settlement south of Torreon.

FLOODS.

In the entire basin there are no permanent streams except the tiny ones just mentioned, but there are many wide stream channels, or arroyos, which are normally dry but which during heavy storms carry water. The water of most of these floods is lost in the arroyos, but that of a few of the largest reaches the central flat and there soaks into the earth. Probably these floods furnish most of the ground water in the valley fill.

UNDERFLOW.

Though the valley includes no important permanent surface stream it contains a great body of ground water which, below a certain depth,

fills every pore, crack, and crevice. From time to time this great body of water receives contributions from portions of the rainfall that escape evaporation. It is not, however, a stationary mass, for it moves constantly though very slowly away from the upland border and toward the low central portion of the basin.

OVERFILLING OF UNDERGROUND RESERVOIR.

If the ground water is constantly augmented by contributions from the rainfall, and if this newly acquired water moves constantly toward the center of the valley, it would be expected that in the central region the pores and crevices of the ground above the bed rock would eventually all become filled and the underground reservoir would overflow. This is essentially what takes place, the surplus being returned to the surface or brought so near to the surface that it can be reached by evaporation. The surplus is disposed of in three ways—(1) by overflow from valley springs; (2) by evaporation from the salt basins; and (3) by evaporation directly from the ground water wherever it rises near enough to the surface to come within the reach of the atmosphere through capillarity. In each of the three ways the ground water is returned to the atmosphere by evaporation.

Where the ground water lies sufficiently near the surface it is withdrawn in the same manner and by the same process that kerosene is withdrawn through the wick of a burning lamp. The soil is the wick. The moisture at the top of the soil is constantly being removed by evaporation just as the kerosene at the top of the wick is removed by burning, and new moisture is drawn up through the pores of the soil just as new kerosene is drawn up through the pores of the wick. In both cases the liquid is lifted by capillarity. But the height to which a liquid can be thus raised is greater for small pores than for large ones. Thus, water can be lifted higher, although less rapidly, in a clay soil, which has small pores, than in a sandy soil, which has large pores.

It is not now possible to make an estimate of the height to which capillarity is effective in the soils of Estancia Valley or of the quantity of water withdrawn from the underground store by this process, but the quantity is undoubtedly large. Near the McGillivray well in Estancia, where the ground water is only about 5 feet below the surface, incrustations of salt were observed, although similar incrustations were not seen in places in the same locality where the depth to ground water is greater. Incrustations are not found on the red soil that lies at a higher level to the west nor, as a rule, on the "ashy" soil which lies at a lower level to the east. East of Moriarty, also, there are areas in which water lies at shallow depths and which show traces of salt at the surface, such as are not generally found in the central part of the valley. The explanation seems to be that in areas where

the depth to ground water is slight the water is drawn to the surface, where it evaporates and leaves its content of salt. (See discussion of quality of the water, pp. 17–23.)

GROUND-WATER TABLE.

Over an area of about 240 square miles (including the salt basins) the ground water stands within 25 feet of the surface; over an area of about 210 square miles it stands between 25 and 50 feet below the surface; and over an area of about 250 square miles it stands between 50 and 100 feet below the surface. Thus over a total area of about 450 square miles it is less than 50 feet below the surface, and over a total area of at least 700 square miles it is less than 100 feet below the surface. The area in which it lies less than 50 feet below the surface includes the low central plain and extends far up the large arroyos, especially Arroyo Mesteno.

RECOVERY OF GROUND WATER.

In the foregoing pages it has been shown that the ground water constantly receives new supplies on the high land and that it migrates slowly but constantly toward the valley, where the excess is disposed of by evaporation. On its way a small amount is at present intercepted and pumped to the surface. The practical question is, To what extent can the water be thus recovered for use? Two phases of this question will here be considered—(1) the yield of wells and (2) the total amount of water available.

YIELD OF WELLS IN THE VALLEY FILL.

A large amount of miscellaneous information in regard to the yield of wells was collected, but unfortunately the bulk of this information is of little value because few wells have been sunk deep enough to reach the best water horizons, and most of the pumping tests have not exceeded a few gallons a minute. Several rather conclusive tests were, however, reported, and, through the generous assistance of R. B. Cochran, of Estancia, a few others were made in the course of this investigation.

Throughout most of the valley there is no difficulty in obtaining a supply that is ample for domestic and stock uses, but in a few localities even this amount is hard to obtain. Near the north end of the valley no wells were seen, and the prospects of procuring water except at considerable depths are not encouraging. In general, the yield of wells appears to be better on the west side than on the east side of the valley.

At Willard the Atchison, Topeka and Santa Fe Railway Company has drilled a number of wells. The deepest one entered red sandstone

at 312 feet and was continued in this rock to 440 feet, at which depth the drilling was stopped. Within the first 312 feet there were numerous beds of coarse gravel that supplied water freely. Fourteen 8-inch wells were sunk at intervals of about 120 feet to depths of approximately 200 feet. An air lift was applied to twelve of these wells simultaneously for ten days and nights, practically without stopping, and during this period each well yielded 110 gallons a minute and the water level was temporarily lowered 3 feet.[a] The water is used extensively on locomotive engines and for other purposes, train loads being shipped to points more than 50 miles east. Altogether, the consumption from these wells amounts to about 350,000 gallons a day or 400 acre-feet a year.

On the premises of Mrs. McGillivray, in Estancia, two test wells were put down—a 6-inch well to a depth of 37 feet and a 10-inch well to a depth of 233 feet ending in hard rock. According to the driller, the largest supply of water was found at a depth of 33 feet, where the drill entered a 4-foot bed of gravel, from which the water rose to a point 5 feet below the surface. With a suction pipe extending 16 feet below the water level, the 6-inch well was successfully pumped at a rate approximately 200 gallons a minute.

In the test wells 4 miles east of Estancia the most water was found, according to J. L. Mayo, the driller, in a bed of gravel at a depth of about 215 feet, but when the well was pumped at the rate of 15 gallons a minute the level of the water in the well was considerably lowered. The well of Oscar Hadley, 3 miles north and 4 miles east of Estancia, which is 94 feet deep, is reported to have been tested at about 20 gallons a minute without lowering the water perceptibly. The well of B. W. Honnold, in the SE. ¼ sec. 21, T. 7 N., R. 9 E., which is 140 feet deep, is reported to have been tested at 18 gallons; the 6-inch well of P. M. Rutherford, in the SW. ¼ sec. 27 in the same township, which is 104 feet deep, at 40 gallons; the well of Mr. Campbell, about 5 miles northeast of Estancia, at 40 gallons; and other tests of this kind were reported. On a number of the old ranches water has in the past been pumped from wells with steam engines.

AVAILABLE QUANTITY OF GROUND WATER.

The rate at which wells will yield water is a factor of vital importance in determining the feasibility of recovering ground water on a large scale, but, contrary to the general supposition, it gives little information as to the total quantity available. This quantity is not inexhaustible, as is so freely assumed, but the amount that can be obtained by large pumps, such as are required for extensive irrigation, is sharply limited. The quantity of ground water obtainable can

[a] The data in regard to the test were given by John Knowles, who has charge of pumping tests and construction for the railway company.

not be determined by pumping a few hundred gallons a minute from a well for a short period for the same reason that the quantity of water in a lake can not be determined by applying to it the same pump; and to proceed on the theory that any amount of ground water is available for irrigation is even less wise than to plan an irrigation project without reference to the flow of the stream on which it depends. The essential difference is that the flow of the stream can be readily and accurately measured, but no such precise methods can be applied to ground water, and therefore much more caution must be used in carrying out a project that depends upon ground water.

Some idea of the total quantity of water that is stored underground can be obtained by considering the sections of wells that have been drilled. The average thickness of the water-bearing beds can be multiplied by the total area over which they occur, and this product by the percentage of pore space in the material comprising these beds, but such an estimate will give little information that is of practical value because withdrawals in excess of the new contributions will lower the water level, increase the cost of pumping, and eventually lead to disaster. Estimates of possible annual recovery by man must therefore be based on the annual increment or on the surplus annually disposed of by nature, and not on the total quantity now stored in the earth.

Unfortunately the quantity of water that is annually available in Estancia Valley can not be accurately determined. From the discussion under the heading "Source and disposal" (p. 13), it appears that the surplus now disposed of by nature through evaporation from the salt basins and other areas of shallow water is a substantial quantity. It is difficult to conjecture what percentage of this surplus it would be possible to intercept in wells and to pump to the surface. It can hardly be hoped that more than this surplus is annually available.

QUALITY OF THE WATER.

DISSOLVED SOLIDS.

The rocks which lie near the surface are exposed to weathering agencies that disintegrate and decompose them, thereby forming certain mineral compounds that are more or less soluble in water. The water which falls as rain contains little or no dissolved mineral matter, but when it enters the ground and percolates through the earth it gradually takes into solution those soluble substances with which it comes into contact, and thus it is that ground water always contains dissolved mineral matter. As long as this matter is in solution it is invisible, but when the water is evaporated, as in a tea-kettle or steam boiler or on the surface of the salt basins in Estancia

Valley, it is left behind and forms a crust or scale. Ground waters differ greatly in the total amount of substances they contain in solution and also in the proportions of the different kinds of substances. When, by evaporation of the water or some other cause, these substances are thrown out of solution, they form mineral salts, such as calcium carbonate (limestone), calcium sulphate (gypsum), sodium carbonate (black alkali), sodium sulphate (Glauber's salt), and sodium chloride (common salt).

METHODS OF INVESTIGATION.

During the progress of the field work 84 samples of water were collected and examined for their content of the carbonates, bicarbonates, sulphates, and chlorides. They were chosen from wells or other sources which would aid most in interpreting the quality of the ground water for the entire region. Thus they were obtained from all parts of the valley, but were taken in largest numbers in the central area, where the mineral content varies greatly within short distances and where its consideration is important in connection with irrigation. The assays were made in the field by means of the apparatus and methods described in Water-Supply Paper 151. In order to have some check on the work, and also to have a basis for judging the relative amounts of calcium, magnesium, sodium, and potassium, a single sample was sent to Prof. J. R. Bailey, of the University of Texas, for complete analysis in the laboratory. This sample was taken from the well of H. N. Summers, 6 miles east of Estancia, in the region where it was especially desirable to know the relative amounts of mineral substances in the deeper waters. The following table gives the complete analysis, and for purposes of comparison the field assay of a sample taken from the same well on the same day:

Analysis and field assay of water from well of H. N. Summers, 6 miles east of Estancia.

Ions.	Parts per million.	
	Sample assayed in the field.	Sample analyzed in the laboratory.
Silica (SiO_2)		19
Iron (Fe)		.05
Aluminum (Al)		Trace.
Calcium (Ca)		200
Magnesium (Mg)		114
Sodium (Na)		274
Potassium (K)		3.8
Carbonate radicle (CO_3)	0.0	.0
Bicarbonate radicle (HCO_3)	243	306
Sulphate radicle (SO_4)	553	755
Chlorine (Cl)	393	390
Total solids		1,956
Temporary hardness as $CaCO_3$		251
Free carbon dioxide (CO_2)		8.8

The field determination agrees closely with the laboratory analysis in the content of chlorine, but there are considerable discrepancies in the bicarbonate and sulphate determinations. The bicarbonate determination is a simple volumetric process with a definite end point, and the assays probably gave results that are fairly accurate relative to each other. Despite these discrepancies, the field assays are of value, especially in throwing light on the problem of the utility of the water for irrigation, a problem in which it is desirable to have tests from as many localities as possible, but in which great precision is not required.

The table on pages 22–23 presents the results of the 84 field assays.

CHLORINE.

In general the chlorine content of these waters is proportionate to the amount of common salt that would be deposited by their evaporation. The ground waters of Estancia Valley differ widely in this respect, the samples analyzed ranging from 7 parts to 16,442 parts per million in the amount of chlorine that they contain.

The analyses show the following conditions: (1) That the water underlying the western slope (including nearly all of the western alluvial slope and most of the littoral zone) contains small quantities of common salt, the chlorine content being uniformly less than 25 parts per million; (2) that in this large area the amount of salt does not increase notably from the foothills toward the center; (3) that throughout a small area in the center of the valley the chlorine content is very great, some of the shallow water being so salty that it can not be used for watering stock; (4) that between the first and the second area there is a zone of fairly pure water which averages about 3 miles in width but which has a tendency to extend some distance up the arroyos; and (5) that on the east side of the valley the water is somewhat higher in its content of salt than on the corresponding west slope. The transition from the fairly pure water of the intermediate zone to the strongly saline water in the central area is remarkably abrupt; so that on the west side, where there are many wells, it is possible to outline with some definiteness the limits of the area in which the water has more than 1,000 parts of chlorine. The abruptness of this transition is shown by assay No. 59 (J. B. Striplin) and assay No. 61 (J. W. Kooken), given in the table (p. 23). The first sample, coming from a well that is in the intermediate area, showed only 219 parts of chlorine; the second, taken from a well a quarter of a mile farther east, showed 5,276 parts.

In the central area the shallowest water is the most strongly saline, and the water from deeper sources is, as a rule, much better. However, no definite law of variation with depth could be established, and it is altogether probable that in some of the deeper wells a certain

amount of shallow water is admitted by imperfect casing and mingles with the deep water that forms the principal supply. Within the area in which the shallow water contains more than 1,000 parts, 9 samples were taken from cased wells in which, so far as could be ascertained, the water came from more than 25 feet below the ground-water level. In these 9 samples the chlorine content ranged from 234 parts to 932 parts and averaged 595 parts, whereas 6 samples of shallow water within the same area ranged from 1,165 parts to 16,442 parts and averaged 7,063 parts, or more than 12 times as much as in the deeper waters.

Finally, it is important to note that the deep waters in the central area are much saltier than the waters from wells on the surrounding slopes. Thus, 34 samples were taken on the west side in the area of less than 25 parts per million, which includes nearly all of the extensive region lying west of the Santa Fe Central Railway. In these 34 widely distributed samples the chlorine content ranged from 7 to 25 parts and averaged 16 parts, a result which should be compared with that of the assays of the 9 samples of deep waters in the central area in which the chlorine ranged from 234 to 932 parts and averaged 595 parts, or 37 times as much.

CAUSE OF SALINITY.

The salinity of the water in the central area results from the process described under "Source and disposal." The ground water is constantly being replenished at the borders by rainfall; responding to the force of gravity, it constantly moves valleyward; and in the low central area the accumulating surplus is constantly coming to the surface and being disposed of by evaporation. In its migration through the earth it picks up a load of salt which it takes into solution, and when it evaporates it leaves this salt behind, thus adding to the salinity of the remaining water or to the amount of alkali in the soil.

But the precise reason for the existing conditions is not so evident. In most of the area in which the sheet of saline water occurs the ground-water level is too far below the surface for capillarity to be effective in drawing up ground water within the reach of evaporation. Thus, in the wells from which were taken the 6 samples that were tested, the depth to water ranges from 7 to 36 feet, and capillarity is probably not effective for depths of more than 5 feet and quite certainly not for depths of more than 10 feet. Moreover, the salts drawn up by capillary action would be deposited near the surface where evaporation would occur, and it is not obvious how they would be carried back so as to contribute to the salinity of the ground water. It is also necessary to account for the salt content in the deeper waters at the center. The most reasonable hypothesis is

that at various horizons in the valley fill of the central area there are beds which are impregnated with salt that was deposited by evaporating waters at the time they were formed, and that afterward these beds became buried under new accumulations of valley fill. It is not unlikely that the shallow sheet of brine coincides approximately with a buried salt deposit laid down at the bottom of the ancient lake at a certain stage of its existence. This hypothesis will also explain the sharp boundary of the area.

EFFECT OF DISSOLVED SOLIDS.

Small amounts of the constituents commonly found in natural waters are not harmful to health. Chlorides are not objectionable in drinking water if only 50 to 100 parts per million are present, but amounts clearly perceptible to the taste render water unpalatable. Magnesic or sodic sulphated waters are laxative, and excessive magnesium or sodium content renders water unfit for man and beast. The worst form of alkali water—that containing alkaline carbonates—was not found in this region.

Calcium and magnesium render water hard and therefore poor for toilet and laundry uses. Bicarbonate and an equivalent quantity of calcium and magnesium are removed from water by boiling, but the calcium and magnesium in excess of this amount, such as would be present in gypsiferous waters, can not be precipitated by boiling. Sodium and potassium do not consume soap and therefore do not make water hard.

Water containing relatively large amounts of most kinds of dissolved mineral matter is tolerated by plants. Among the common sodium salts, the most injurious is sodium carbonate and the least injurious is sodium sulphate; sodium chloride occupies an intermediate position. The effect of dissolved solids in irrigation water is more fully discussed under the next heading—"Irrigation."

Chemical analyses of water in Estancia Valley.

[Field assays. Parts per million unless otherwise stated.]

No.	Owner.	Location.	Description of well.	Depth of well.	Depth to water.	Carbonate radicle (CO_3).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).[a]	Chlorine (Cl).
				Feet.	*Feet.*				
1	Cedar Vale well	SW. ¼ sec. 27, T. 2 N., R. 12 E.	Drilled, partly cased	298	174	0	424	>625	55
2	Mountainair village well	Mountainair	Drilled	303		0	212	157	9
3	Elijah Bradley	NE. ¼ sec. 11, T. 3 N., R. 9 E.	do	100	80	0	170	>625	25
4	Progreso well	SW. ¼ sec. 15, T. 3 N., R. 10 E.	Dug		35	0	158	574	33
5	J. S. Penny	NE. ¼ sec. 1, T. 4 N., R. 6 E.	do	50	45	0	206	<30	13
6	S. R. Seymour	SW. ¼ sec. 8, T. 4 N., R. 7 E.	Drilled	110	55	0	170	<30	17
7	S. R. Seymour	NE. ¼ sec. 11, T. 4 N., R. 7 E.	do	150	110	0	218	<30	13
8	J. B. Vincent	NE. ¼ sec. 23, T. 4 N., R. 8 E.		95	93	0	194	160	24
9	E. P. Parker	NE. ¼ sec. 24, T. 4 N., R. 8 E.	Dug		63	0	146	146	20
10	E. P. Parker	SE. ¼ sec. 24, T. 4 N., R. 8 E.	do		66	0	158	181	18
11	W. R. Walden	NE. ¼ sec. 26, T. 4 N., R. 8 E.	do	120	105	0	158	181	18
12	Ranch	NE. ¼ sec. 32,[b] T. 4 N., R. 8 E.				0	121	>625	25
13	Eugene Forbes	SE. ¼ sec. 6, T. 4 N., R. 9 E.	Dug	40	40	0	194	197	31
14	Atchison, Topeka & Santa Fe Ry. wells at Willard.	NW. ¼ sec. 8, T. 4 N., R. 9 E.				0	218	238	46
15		NW. ¼ sec. 11, T. 4 N., R. 9 E.	Dug		8	0	291	>625	417
16	A. P. Hanna	NW. ¼ sec. 31, T. 4 N., R. 9 E.	do	98	85	0	109	>625	17
17	Ranch	SW. ¼ sec. 3, T. 4 N., R. 10 E.	do		30	0	412	>625	1,165
18	Ranch	Sec. 33,[b] T. 4 N., R. 10 E.				0	133	383	40
19	J. B. Teague	SE. ¼ sec. 17, T. 5 N., R. 7 E.		115	93	0	230	<30	9
20	Ranch	SW. ¼ sec. 33, T. 5 N., R. 7 E.	Dug		15	0	327	35	17
21	L. Knight	NE. ¼ sec. 1, T. 5 N., R. 8 E.	Large dug hole	27	20	0	243	80	15
22	Thomas Elgin	SW. ¼ sec. 6, T. 5 N., R. 8 E.	Dug		82	0	182	<30	7
23	Thomas Elgin	NE. ¼ sec. 35, T. 5 N., R. 8 E.	do		31	0	267	42	15
24	Thomas Elgin	NE. ¼ sec. 18, T. 5 N., R. 9 E.	6-inch, with casing	36	24	0	545	478	65
25	E. L. Moulton	SE. ¼ sec. 13, T. 5 N., R. 10 E.	Drilled and cased	120	95	0	121	>625	141
26	Fletcher Brown	SW. ¼ sec. 4, T. 5 N., R. 11 E.	Drilled with casing	84	65	0	340	406	261
27	Stream	Sec. 26,[b] T. 6 N., R. 6 E.					158	<30	10
28	Spring in foothills	Sec. 34,[b] T. 6 N., R. 6 E.				0	388	<30	7
29	Porter ranch	SW. ¼ sec. 34, T. 6 N., R. 7 E.		125	100	0	218	<30	7
30	L. C. Weaver	NW. ¼ sec. 1, T. 6 N., R. 8 E.	Not cased	40	26	0	679	328	140
31	R. B. Cochran	SW. ¼ sec. 11, T. 6 N., R. 8 E.	Dug		13	0	267	<30	5
32	Estancia Spring	SE. ¼ sec. 11, T. 6 N., R. 8 E.				0	291	<30	17
33	Box factory, Estancia	NW. ¼ sec. 12, T. 6 N., R. 8 E.	Cased to 59 feet		20	0	873	>625	251
34	W. J. Adair	NW. ¼ sec. 12, T. 6 N., R. 8 E.	Dug		18	0	631	574	693
35	Valley Hotel, Estancia	SW. ¼ sec. 12, T. 6 N., R. 8 E.				0	329	383	54
36	N. E. Bilsing	SE. ¼ sec. 13, T. 6 N., R. 8 E.		12	9	0	243	344	84
37	H. C. Williams	NE. ¼ sec. 26, T. 6 N., R. 8 E.	Dug		6	0	243	50	20
38	H. C. Williams	NE. ¼ sec. 26, T. 6 N., R. 8 E.	Drilled and cased	318	4	0	533	66	139
c39	H. N. Summers	SW. ¼ sec. 1, T. 6 N., R. 9 E.	3-inch casing to 45 feet	65	10	0	243	431	438
c40	H. N. Summers					0	243	553	393

41	N. Williams	SE. ¼ sec. 3, T. 6 N., R. 9 E.	Cased	26	9	0	364	>625	914
42	T. J. Moore	SW. ¼ sec. 5, T. 6 N., R. 9 E.	Dug		13	0	340	383	80
43	Mrs. N. L. Williams	NE. ¼ sec. 10, T. 6 N., R. 9 E.	Cased	32	7	0	303	>625	15,075
44	Unsuccessful test well	SW. ¼ sec. 10, T. 6 N., R. 9 E.	Cased to 205 feet	215	7	0	533	553	784
45	A. Abbott	SE. ¼ sec. 11, T. 6 N., R. 9 E.	Cased to 100 feet	159	5	0	243	328	309
46	Charles May	NE. ¼ sec. 12, T. 6 N., R. 9 E.	Dug	20	20	0	259	>625	16,442
47	A. Abbott	SE. ¼ sec. 15, T. 6 N., R. 9 E.	Cased to 120 feet	156	6	0	424	553	603
48		SW. ¼ sec. 15, T. 6 N., R. 9 E.	do	156	5	0	582	553	932
49	J. J. Smith	NW. ¼ sec. 19, T. 6 N., R. 9 E.	Drilled, 6-inch casing	60	8	0	315	91	40
50	W. H. Hancock	NE. ¼ sec. 20, T. 6 N., R. 9 E.	Drilled and cased	90		0	679	625	603
51	C. B. Cornell	SW. ¼ sec. 28, T. 6 N., R. 9 E.	Not cased	18	14	0	728	>625	269
52	A. L. Bilsing	N. ½ sec. 33, T. 6 N., R. 9 E.	Drilled and cased	100	14	0	752	>625	587
53	William Dunbar	Sec. 4,[b] T. 6 N., R. 10 E.		50	47	0	194	553	283
54		Sec. 26,[b] T. 6 N., R. 10 E.	Dug		36	0	218	625	2,412
55	E. F. Heal	SE. ¼ sec. 31, T. 6 N., R. 11 E.	do	60	50	0	194	492	361
56	J. B. Gwaltney	SE. ¼ sec. 36, T. 7 N., R. 7 E.	Drilled	139	135	0	170	<30	13
57	Antelope Spring	SW. ¼ sec. 14, T. 7 N., R. 8 E.				0	364	<30	20
58	M. Freilinger	SW. ¼ sec. 24, T. 7 N., R. 8 E.	Dug		35	0	340	42	55
59	J. B. Striplin	SE. ¼ sec. 20, T. 7 N., R. 9 E.	Dug		10	0	267	265	219
60	B. W. Honnold	SE. ¼ sec. 21, T. 7 N., R. 9 E.	Drilled and cased	140	12	0	243	383	234
61	J. W. Kooken	NW. ¼ sec. 28, T. 7 N., R. 9 E.	Not cased		10	0	680	>625	5,276
62	T. J. Curtis	SE. ¼ sec. 30, T. 7 N., R. 9 E.	Dug		10	0	352	287	85
63	Duncan McGillivray	NE. ¼ sec. 8, T. 7 N., R. 10 E.	Drilled	93	56	0	133	150	40
64	E. F. Moore	SW. ¼ sec. 15, T. 7 N., R. 10 E.			66	0	170	256	65
65	Allan McGillivray	Sec. 31, T. 7 N., R. 11 E.	Drilled	120	45	0	97	>625	60
66	S. C. Keehnel	SE. ¼ sec. 36, T. 8 N., R. 7 E.		140	85	0	279	30	25
67		NW. ¼ sec. 1, T. 7 N., R. 8 E.	6-inch, not cased		30	0	315	43	25
68	John T. Lee	NW. ¼ sec. 28, T. 8 N., R. 9 E.	Not cased	25	22	0	218	460	319
69	J. O. Justus	SW. ¼ sec. 33, T. 8 N., R. 9 E.	do	25	20	0	291	625	2,010
70	Ranch	SE. ¼ sec. 8,[b] T. 9 N., R. 8 E.			34	0	194	<30	10
71	Michael T. Moriarty	NE. ¼ sec. 22, T. 9 N., R. 8 E.	Dug	32	21	0	218	82	301
72	W. C. Maurer	NW. ¼ sec. 1, T. 9 N., R. 9 E.	Drilled	70	63	0	158	460	274
73	Robert Hickman	SE. ¼ sec. 4, T. 9 N., R. 9 E.	Not cased	30	26	0	170	460	251
74	Edith B. Rush	SW. ¼ sec. 29, T. 9 N., R. 9 E.	Dug		16	0	206	574	222
75	B. Hill	NW. ¼ sec. 28, T. 9 N., R. 10 E.	Drilled	189		0	194	197	20
76	A. Stewart	NW. ¼ sec. 21, T. 10 N., R. 8 E.	do		127	0	206	<30	10
77	R. H. Harper	NE. ¼ sec. 34, T. 10 N., R. 8 E.	do	100	74	0	194	34	15
78	S. E. Kelly	NW. ¼ sec. 3, T. 10 N., R. 9 E.	do		99	0	194	61	13
79	John H. Cantwell	NW. ¼ sec. 5, T. 10 N., R. 9 E.	do	103	75	0	170	95	13
80	E. H. Clayworth	SW. ¼ sec. 27, T. 10 N., R. 9 E.	Dug		27	0	146	383	119
81	G. W. Hearte	NE. ¼ sec. 5, T. 10 N., R. 10 E.		180	165	0	243	56	14
82	Deserted ranch	SW. ¼ sec. 1, T. 11 N., R. 8 E.	Dug	250	200	0	182	78	8
83	Stanley village well	Stanley		160	152	0	220	52	13
84	W. C. Asher	do	Drilled	207	100	0	243	94	18

[a] > means more than. < means less than. [b] Approximate location. [c] Samples 39 and 40 were taken from the same well, but at different times and after different rates of pumping.

IRRIGATION.

Much of the water that falls as rain is lost or is of very small service in agriculture. If only a small part of this water that is now lost can be recovered and applied to growing crops it will greatly increase the agricultural product of the valley. Recovery is possible in two ways—(1) by storing storm water, (2) by pumping ground water. The storage of storm water is not here considered.

UTILIZATION OF GROUND WATER.

PRESENT DEVELOPMENT.

At the time the valley was visited (the summer of 1909) little had been accomplished in the way of irrigating with ground water, although a number of gardens and other small plats were being irrigated from this source by means of windmills, and somewhat more ambitious projects were being undertaken by S. Spore, L. Knight, E. A. Von de Veld, and H. C. Williams.

POSSIBILITIES OF FUTURE DEVELOPMENT.

The data already given seem to indicate that, without seriously depleting the present supply, enough water can annually be withdrawn from the underground reservoir to increase materially the total production of the valley, but that, on the other hand, however economically such water may be applied, it is not sufficient in amount to irrigate more than a small part of the total acreage of arable land. If it is once proved that pumping for irrigation is feasible and profitable, the danger of overdevelopment will become imminent.

PROPER TYPE OF IRRIGATION SYSTEMS.

Irrigation with surface water has necessitated large cooperative projects, but the problem of irrigating with ground water, even on a large scale, is essentially different. In Estancia Valley each farmer should develop his own supply, install his own pumping plant, and construct his own reservoirs and system of distribution. This method of development will insure a maximum supply with a minimum lowering of the head, and will involve the least lift and the least loss in distribution. The only respect in which cooperation may be found profitable will be in installing a central power plant.

PROPER TYPES OF WELLS.

Where large supplies are required, as for irrigation, they can best be obtained by drilling in search of thick beds of clean, coarse gravel that will yield freely, if necessary, sinking at least to the bottom of the

valley fill. There are three reasons why deep drilled wells are likely to yield much more water than shallow wells that stop a short distance below the ground-water level: (1) The thickest and best beds of gravel may occur at great depth; (2) of two similar beds the one at a considerable depth below the ground-water level is likely to yield much more than the one only slightly below this level, because the water in the deeper bed is under much greater artesian pressure; (3) if a deep well is properly finished with perforated casing, it can simultaneously receive supplies from all water-bearing beds that it penetrates.

If a single well will not yield enough, a group of wells can be drilled. A large pump can then be inserted at the bottom of a centrally located pit dug to the ground-water level, or somewhat lower, and suction pipes from all the wells can be connected with it; or, if it is desired to use a chain and bucket elevator, the central pit can be sunk to a considerable depth below the ground-water level and the drilled wells can be connected by horizontal tunnels or pipes with the bottom of the pit, into which they will then discharge. Since the cost of pumping increases with the lift, it will be economy to have so many wells that the water in them will not be greatly lowered by pumping. In either system above described some expense will be involved in connecting the various wells.

For large supplies, beds of very fine sand should be cased out, because this sand yields its water slowly and causes trouble by rising in the wells. Screens can be employed to shut out the sand, but they are liable to become clogged in a short time and to require much attention. Difficulty with sand in wells can be brought to a minimum by pumping slowly or by having a large number of wells so connected that water is drawn only slowly from each.

Where no satisfactory water-bearing bed can be found and where the shallow water is not saline it may be possible to obtain valuable supplies from large dug wells or from systems of infiltration galleries, or it may be feasible to bring up the total yield by combining these with deep wells. If possible the maximum yield of the system of wells should be kept much greater than the capacity of the pumps, as this will reduce to a minimum the cost of lifting the water, the wear and tear of the machinery, and in some places the deterioration of the wells.

GRAVITY INFILTRATION DITCHES.

The fact that it is possible to lead water by gravity from the shallow-water belt on the west side out upon lower ground to the east makes this scheme for irrigation appear very attractive, but it is not believed that enough water can be recovered in this way to justify the necessary expense of construction. The same money will be better

invested in wells and a pumping plant with which a larger, more reliable, and more elastic supply can be obtained. Professor Slichter discusses ditches of this type and makes the following concluding statements: [a]

It should be noted that very few infiltration or underflow canals are in actual use for irrigation. Many pumping plants in use for irrigation have turned out to be both practicable and financially profitable, but the attempts to procure ground water by gravity have usually proved disappointing, and there are numerous abandoned underflow canals in many parts of the West.

COST OF PUMPING.

In estimating the cost of the water it is necessary to take into account the original cost of the wells, pumps, engines, reservoirs, ditches, and other equipment, and the cost of operation, which includes fuel, oil, repairs, labor, and other items. In considering the original cost as a factor in the cost of a unit quantity of water it is most convenient to estimate the amount of deterioration of the plant in one year and to add this to the annual interest on the total amount invested in the plant. The sum should then be divided by the number of units of water pumped in a year. Professor Slichter advises that the charge for depreciation and repairs should be estimated at not less than 10 per cent of the first cost of the plant.

The following tables give the results of a number of tests of small pumping plants in the Arkansas Valley, Kansas, [b] and in the Rio Grande valley, New Mexico: [c]

Tests of small pumping plants, Arkansas Valley, Kansas.

Kind of pump.	Horse-power of engine.	Fuel used.	Price of fuel per gallon.	Total lift.	Yield of well per minute.	Cost of fuel per acre-foot[d] of water.	Cost of fuel for each foot that an acre-foot is lifted.
				Feet.	*Gallons.*		
No. 3 centrifugal	6	Gasoline	$0.22	22.1	272	$2.93	$0.13
Menge	10	do	.20	15.5	394	2.90	.19
Two vertical, 6 by 16 inch cylinder.	1½	do	.22	15.06	91	3.75	.25
Chain and bucket	7	do	.21	17.0	540	1.37	.08
Do	2½	do	.22	15.8	215	2.78	.18
No. 4 centrifugal	10	do	.12½	22.13	363	2.10	.09
No. 3 centrifugal	6	do	.12½	17.60	198	1.67	.09
No. 14 centrifugal	80	Coal	[e] 4.00	23.00	2,300	.85	.04
Two horizontal, 5 by 5 inch cylinders.	3½	Gasoline	.12½	21.7	96	1.09	.05
No. 4 centrifugal	5	do	.12½	21.47	420	1.20	.06

[a] Water-Supply Paper U. S. Geol. Survey No. 184.
[b] Slichter, C. S., The underflow in Arkansas Valley in western Kansas: Water-Supply Paper U. S. Geol. Survey No. 153, 1906, pp. 55 and 56.
[c] Slichter, C. S., Observations on the ground waters of the Rio Grande valley: Water-Supply Paper U. S. Geol. Survey No. 141, 1905, pp. 34 and 35.
[d] An acre-foot contains 325,850 gallons of water, which is enough to cover 1 acre to the depth of 1 foot.
[e] Price per ton.

Principal data derived from tests of Rio Grande pumping plants.

Horsepower.	Fuel used.	Price of fuel.[a]	Total lift.	Yield per minute.	Cost of plant.	Interest and depreciation per hour.[b]	Labor and other cost per hour.	Fuel cost per acre-foot.	Total cost per acre-foot.
			Feet.	*Gallons.*					
10	Electricity	$0.05	38.93	378	$1,200	$0.108	$0.050	$3.43	$5.75
8	Gasoline	.14	30.70	269	800	.072	.120	2.26	6.13
5½	....do	.14	27.80	258	800	.072	.140	1.58	6.02
28	Crude oil	.03	36.70	938	3,000	.270	.180	.70	3.17
22	Gasoline	.14	41.45	1,325	2,200	.198	.150	1.43	2.79
15	....do	.14	35.87	658	1,500	.135	.150	1.73	4.10
5	....do	.17	45.58	131	1,200	.108	.120	3.73	13.20
12	....do	.17	40.30	658	1,200	.108	.150	1.34	3.47
21	....do	.17	40.45	725	1,800	.162	.150	2.52	4.87
8	....do	.17	26.85	648	900	.081	.120	1.48	3.16
12	....do	.17	34.77	325	1,200	.108	.150	5.14	9.57
8	....do	.17	36.05	271	800	.072	.120	5.10	8.95
10	Wood	2.00	34.16	351	1,200	.108	.180	3.47	7.91
28	Gasoline	.17	43.35	464	2,000	.180	.150	4.34	8.19
20	Wood	2.25	29.55	1,000	1,600	.144	.200	2.83	4.70
12	Gasoline	.17	23.89	837	992	.090	.090	1.04	2.21
12	....do	.17	35.26	191	992	.090	.090	5.80	10.90
12	....do	.17	32.36	750	992	.090	.090	1.16	2.46

[a] The price of gasoline given is for 1 gallon, the price of electricity for 1 kilowatt-hour, the price of wood for 1 cord.

[b] The depreciation and repairs are calculated at 10 per cent of the original cost and the interest at 8 per cent.

As near as it can be estimated from rather indefinite data obtained in regard to the plant of E. A. Von de Veld, northwest of Willard, the cost of fuel is about $3.50 an acre-foot. The water is here lifted with a 160-gallon chain and bucket elevator; the average lift is about 30 feet, and the price paid for the gasoline was reported to be 31 cents per gallon. According to these data, for each foot that an acre-foot of water is lifted the cost is about $1\frac{2}{3}$ cents and the consumption of gasoline about 0.38 gallon. With the present capacity of the well, one-fifth of an acre-foot can be drawn conveniently in one full day; and on this basis if the plant is operated one hundred days it will consume $65 worth of gasoline and provide enough water to cover 20 acres to a depth of 1 foot or 10 acres to a depth of 2 feet. With gasoline bought at minimum wholesale prices and with more careful adjustments between the capacities of engine, pump, and well, the cost for fuel can be reduced materially, but the above figures are believed to be valuable in giving an idea of what has been done in practical work.

In a discussion of the cost of pumping in Arkansas Valley, Kansas, the following statement is made by Professor Slichter in regard to gas-producer plants:

If plants of from 20 to 50 horsepower are constructed, as I believe they will inevitably be in the near future, the cheapest power will probably be found in the use of coal in small gas-producer plants in connection with gas engines. These small gas-producer plants are largely automatic in action and can be operated by anyone. With hard coal or coke or charcoal at $8 per ton, the cost of power would be less than one-half cent per horsepower for one hour, or only one-fifth of the cost of power from gasoline at 22 cents a gallon. The writer anticipates no difficulty, therefore, in keeping the cost of water

below 60 to 75 cents an acre-foot for fuel, or below $1.25 to $1.50 per acre-foot for total expense.[a] Hundreds of such plants have been put in use in England during the past ten or more years, and they are in charge of unskilled labor. These gas-producer plants are used in England for a great variety of purposes, such as power for agricultural machinery and for small electric-light plants for country estates. They are used in as small units as 5 horsepower.

In this country the producer-gas plants have been in use for several years, and at the present moment they are fast taking the place of steam power in new plants. The cost of a producer plant and gas engine is about the same as the cost of a steam engine and boiler of same size when everything is included, but the cost of power from the producer-gas plant is very much less than that obtained from small steam engines.

In producer plants ranging upward from 100 horsepower a style of plant may be installed in which soft coal or lignite may be successfully used. This still further cuts down the cost of power. In fact, large plants of this type furnish the cheapest artificial power that has yet been devised. The saving is not only in fuel, but also in labor, as one man is capable of running a 300-horsepower plant.

In Estancia Valley gas-producer plants should be installed only after sufficiently large supplies of water have been developed to insure the success of such plants. A central power plant which will furnish an electric current for operating pumps on a number of farms may prove the most economical method of lifting water.

WINDMILLS.

Much has been written on irrigation with windmills. Their obvious advantage is that they utilize energy which is supplied by nature free of charge, but their original cost and the cost for oil and repairs are by no means negligible. Their greatest disadvantage lies in their dependence upon the wind, which may not blow at the time the water is most needed. They are best adapted to those parts of the valley where great depth to water or small yield permit irrigation on only a small scale.

The following data, taken from the Yearbook of the Department of Agriculture for 1907, will give some conception of what can be done with windmills. If the lift is increased or decreased, the amount of water that can be pumped will be decreased or increased in about the same ratio.

Work done by a 12-foot windmill.

Velocity of wind in miles per hour.	Height water was lifted.	Quantity of water pumped per hour.
	Feet.	*Gallons.*
6	56	89.76
8	56	269.28
10	56	501.16
12	56	718.08
17	56	1,271.60
18	56	1,353.88

[a] It should be remembered that this statement is made for the Arkansas Valley, where the water is near the surface.

Work done by windmills of different sizes.

Size and type of windmill.	Time.	Average wind velocity per hour.	Height water was lifted.	Quantity of water pumped.	
	Days.	*Miles.*	*Feet.*	*Gallons.*	*Acre-feet.*
16-foot, direct stroke	45½	12.98	56	752,967	2.31
14-foot, back geared	45½	12.98	56	666,991	2.05
13-foot, back geared	45½	12.98	56	502,207	1.54
12 foot, back geared	45½	12.98	56	408,854	1.25

VALUE OF CROPS.

Intensive cultivation of crops that yield large returns per acre would, of course, leave the largest margin after the cost of the water is deducted and would thus guarantee the surest success for irrigation by pumping, but present calculations must be based upon such ordinary field crops as can be depended upon in respect to both yield and market value. It is not intended here to enter into a full discussion of the various crops that might be raised, but rather to state a few facts which will give some quantitative basis for comparing crop returns with cost of water.

In regard to alfalfa, Samuel Fortier,[a] chief of irrigation investigations in the Department of Agriculture, states:

> Perhaps the most essential conditions for the production of alfalfa are abundant sunshine, a high summer temperature, sufficient moisture, and a rich, deep, well-drained soil. All of these essentials, save moisture, exist naturally in the arid region of the United States, and when water is supplied it makes the conditions ideal. * * * It is grown successfully in every State and Territory of the arid region, in localities which are not only widely separated but possess many radical differences in the way of rainfall, temperature, altitude, topography, and soil.

Mr. Fortier cites an experiment in Montana in which with 1 foot of irrigation water 4.42 tons of cured alfalfa per acre were produced, and with 2 feet, 6.35 tons, and adds:

> The results of this experiment seem to confirm the best practice of southern California, which may be summed up by stating that in localities having an annual rainfall of about 12 inches remarkably heavy yields of alfalfa may be obtained from the use of 24 to 30 inches of irrigation water providing it is properly applied.

C. A. Fisher[b] states that in the vicinity of Roswell, N. Mex., if 30 inches per year are properly applied, three or four crops of alfalfa may be cut, an average yield being 1 ton to the acre for each cutting. V. L. Sullivan, territorial engineer of New Mexico, estimates[c] that "the yield of hay (alfalfa) in this part of the United States is 2 to 7 tons an acre when grown under irrigation; an average of 5 tons is a conservative estimate, usually producing a net return of $10 per ton."

[a] Irrigation of alfalfa: Farmers' Bull. No. 373, U. S. Dept. Agr., 1909.

[b] Geology and underground waters of Roswell artesian area, New Mexico: Water-Supply Paper U. S. Geol. Survey No. 158, 1906, p. 28.

[c] Irrigation in New Mexico: Farmers' Bull. No. 215, U. S. Dept. Agr., 1909, p. 17.

Alfalfa seed is a valuable though rather uncertain crop, but it requires little water and could perhaps be raised to advantage after one crop of hay had been harvested.

Good crops of wheat, oats, and other cereals could no doubt be raised by irrigation, but a given amount of water would probably accomplish more if applied to beans, potatoes, or forage plants such as cane, Milo maize, and kaffir corn. Beets, melons, and vegetables are said to thrive well when moisture is applied, and some kinds of fruit could be raised.

BEST USE OF THE WATER.

The most hopeful view of the future of irrigation in Estancia Valley can not alter the conclusion that this valley must remain essentially a grazing or dry-farming region. Grazing yields very small returns per acre; dry farming may, if the elements happen to be propitious, yield vastly more. But the elements are and always will be capricious, and the farmer who must depend upon them entirely will necessarily have a precarious lot. The available water will, of course, be utilized in various ways, but it would seem that in the main it would be put to its best use when it is employed to supplement dry farming and stock raising.

In the first place, every farmer should irrigate a few shade trees, a small orchard, a small grass lawn, and a garden containing vegetables, shrubs, and flowers. These things will contribute much to the comfort of farm life, and, moreover, the garden will be of substantial value in supplying food for the household and in making it possible to tide over dry years. One of the very few examples of such irrigation at present found in the wide expanse of the valley is at the old Moriarty ranch. A small supply of water will provide these essentials. Indeed, there are few localities in the valley where enough water can not be obtained, or where it is so deep that the farmer can not afford to pump it for this purpose. For this kind of irrigation windmills will be useful, but it will be well to supplement them by small gasoline engines, so that the supply will not fail at the time it is most needed.

Where plentiful supplies of water are available within a comparatively short distance of the surface it may be profitable to install a larger plant and to irrigate a number of additional acres, on which can be raised alfalfa or forage, which will have a high value if fed to the stock on the farm in the winter or in times of extreme drought, when otherwise the stock would suffer severely; or a portion of the water can be used to raise for the market some more intensive crop, such as beans or potatoes, the proceeds of which will help to tide over years of failure in dry farming.

More than this, it may be that the ground water can be used to some extent to supplement dry farming directly. The damage to

crops is due perhaps less to the absolute deficiency of rainfall than to its irregularity and uncertainty. For example, enough rain may fall throughout the growing season to produce a fair yield except in one period of drought. If during this period the ground could be given one good wetting, success would be assured; but the wetting does not come and the farmer stands helplessly by to see his crop a total failure. It requires no argument to show that irrigation water at this critical time would have a value out of all proportion to that of its ordinary crop-producing power. It is also evident that a relatively small amount of water, considered for the entire year, would cover a large acreage; and it will be readily appreciated by the dry farmer who has gone through the hard experience of seeing his entire crop ruined that if, by means of the artificial application of water, only a small portion of his crop can be saved, it will be infinitely better than failure. There will, of course, be difficulties in developing a feasible method of combining irrigation and dry farming, but there appears to be no inherent reason why such a combination method can not be evolved.

The limits to the area in which the larger use of water is practicable and the limits to the amount of irrigation that is possible in any given locality within this area must be determined gradually by experience. The situation tends strongly toward an economical use of the water, and economy will tend in two ways to enlarge the scope of irrigation. It will reduce to a minimum the expense of pumping and the waste of the limited underground supply. The first concerns the immediate welfare of the individual; the second concerns the permanent welfare of the entire community. To a certain extent individual self-interest will here abet the public welfare, for the pump will not be operated except when necessary.

THE ALKALI PROBLEM.

The answer to the question whether a certain quality of water can be successfully used for irrigation depends largely on a number of related conditions, among which may be mentioned the kind of crops to be raised, the amount of alkali already in the soil, the natural drainage of the land or the ease with which artificial drainage could be established, and the cost and abundance of the water itself. If all these conditions are favorable, water containing large amounts of sodium sulphate and sodium chloride can be used with success, but if all or most of them are unfavorable the case is entirely different.

During the summer of 1902 T. H. Means, of the Bureau of Soils, visited certain oases in the Sahara Desert in eastern Algeria, in which waters carrying large quantities of soluble matter are used successfully for irrigation. Some of the vegetables successfully grown are

those considered sensitive to alkali, and yet they were being irrigated with water containing, in some places, as much as 8,000 parts per million of soluble salts, sometimes as much as one-half of these salts being sodium chloride. The methods used are described as follows: [a]

The Arab gardens are divided into small plots, about 20 feet square, between which run drainage ditches dug to a depth of about 3 feet. The soils being very light and sandy, this ditching at short intervals insures the most rapid and thorough drainage. Irrigation is by the check method, and application is made at least once a week, though often two wettings a week are deemed necessary. A large quantity of water is used at each irrigation. Thus a continuous movement of the water downward is maintained, there is little opportunity for the soil water to become more concentrated than the water as applied, and the intervals between irrigations being so short but little accumulation of salt from evaporation at the surface takes place. What concentration or accumulation does occur is quickly corrected by the succeeding irrigation.

It is essential to note that the successful use of this water depends entirely upon good drainage conditions and the application of large amounts of water. In the same paper, Means says:

The limit for concentration for irrigation water in the United States, even where only the most resistant crops are to be grown, has been placed by some authorities at 300 parts sodium chloride (common salt) or sodium carbonate (black alkali) and at from 1,700 to 3,000 parts of the less harmful salts, per million of water.[b] Those who place the low limit of safety for alkaline irrigation waters have taught that where water was badly alkaline irrigation should be sparing. They have not insisted on thorough drainage, and they have warned irrigators against too frequent irrigation. With such practices the limit of concentration which they set is probably high enough, and even then all except the most sandy soils or those with exceptionally good natural drainage would ultimately be damaged.

Writing upon the same subject, C. N. Dorsey says: [c]

When the soil contains a relatively large amount of salt and but little water containing much salt is frequently applied, the ordinary evaporation will increase the salt content of the soil to such an extent that crops can no longer survive, whereas if adequate drainage is provided and a large amount of water is used the excess of salt resulting from the evaporation of previous applications of water may be removed and the soil moisture be maintained at nearly the same concentration as the water supply.

The data given under "Soil" and "Quality of water" furnish a basis for a rather definite conclusion in regard to the feasibility of irrigating in the alkali area of Estancia Valley. The samples of soil that were analyzed have a high alkali content, and the water in the same region is rich in dissolved chlorides and sulphates. Within the area of saline shallow water (that is, the area in which the shallow ground water has a chlorine content of more than 1,000 parts per million), 9 samples of deeper water were tested, and the average chlorine content of these 9 samples was found to be 595 parts per million. On the assumption that all the chlorine is in equilibrium

[a] Means, T. H., The use of alkaline and saline waters for irrigation: Bureau of Soils Circular No. 10, U. S. Dept. Agr.

[b] In the original paper the quantities are expressed in parts per 100,000 of water.

[c] Reclamation of alkali soils: Bull. Bureau of Soils No. 34, U. S. Dept. Agr., 1906, p. 11.

with sodium, the average content of common salt would be 982 parts per million, or more than 2,500 pounds per acre-foot. By the time 10 feet of water would have been applied to a field, 25,000 pounds of common salt would have been placed on each acre irrigated, which would be 0.625 per cent of the soil if concentrated in the first foot, or 0.156 per cent if distributed through the upper 4 feet.

If good drainage conditions could be established and the water could be applied unsparingly, then, by the use of the deeper water, the alkali now in the soil and that introduced by the water could be disposed of by leaching it downward and draining it away. Unfortunately the natural drainage is poor and the expense of establishing artificial drainage would be too great. Unfortunately, too, the liberal use of water would be prevented by the limitations of the supply and the cost of pumping. In view of these facts the general conclusion can not be avoided that in the most alkaline portion of the central flat irrigation by pumping from wells is not feasible, and it becomes necessary to advise against expenditures for installing pumping plants within this area. A like caution should also be given for a wider region having poor drainage, water of intermediate chlorine content, or soil that shows any alkali symptoms, lest, in the course of time, the sparing application of well water will result in an injurious accumulation of alkali.

SUMMARY.

The conclusions in regard to irrigation with ground water can be briefly summarized as follows:

In spite of the high cost of fuel, if the water is lifted in the most economical way and is wisely used, pumping for irrigation can under favorable conditions be made profitable. The underground supply is too small to irrigate more than a small part of the valley, but it is sufficient to add materially to the prosperity and comfort of the people. Even where the depth to water is great, the irrigation of a garden, lawn, and orchard will generally be feasible. In the central area, however, the presence of alkali may seriously impair the quality of the water or may prohibit its use. Taken as a whole, the water of Estancia Valley is a valuable resource that should be developed, but its development should be conducted carefully and with full cognizance of the inherent limitations.

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